EIT KIC InnoEnergy Master's Programme

Renewable Energy - RENE

MSc Thesis

Analysis to achieve a high penetration of renewable energies in MW-scale electricity Microgrids with the case study of an island in the Pacific

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Abstract

As the penetration of intermittent renewable energies consumed in MW-scale electrical grids becomes high, in many countries reaching more than 25 % per year, the need for control, stabilization and storage methods to guarantee a stable and constant supply at any given moment becomes crucial. Many technological solutions exist in the market. Some are more mature than others. A benchmarking of the grid stabilization and energy storage solutions offered by companies is followed by an overview of islands with an existing or planned high penetration of renewable energies. In a next step, a case study of the transition from a diesel powered towards a renewable energy electricity grid in an island in the Pacific is presented. A final discussion about the techno-economical sense of each solution is made comparing factors such as CAPEX and NPC.

Keywords: Microgrids, NPC, Energy storage, Penetration level, Islands, MW-scale

Table index

Image index

Contents

Glossary

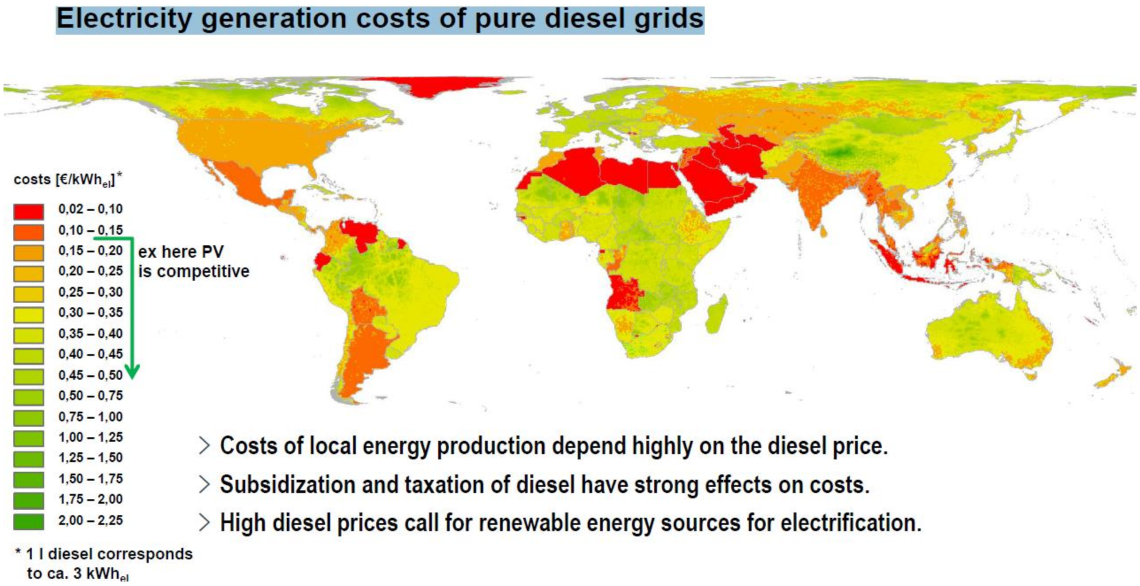
AC	Alternate current
CAPEX	Capital expenditures
CO	Carbon monoxide
DC	Direct current
DOD	Depth of discharge
ESS	Energy storage systems
FSC	Fuel save controller
GW/GWh	Gigawatt/Gigawatt-hour
IEC	International electrotechnical commission
kVA	kilovoltampere
kW/kWh	Kilowatt-hour
kWp	Kilowatt peak
LCOE	Levelised cost of electricity
MENA	Middle East North Africa
Mppt	Maximum power point tracking
MW/MWh	Megawatt/Megawatt-hour
NPC	Net present cost
O&M	Operation and management
OPEX	Operational expenditures
OTEC	Ocean technologies
PEM	Proton exchange membrane
PV	Photovoltaic
SOC	State of charge
VRB	Vanadium redox flow battery

1 Introduction

1.1 Motivation behind the work

1.1.1 Expensive diesel leads to high electricity costs

The price of diesel depends on different factors but especially on the remoteness of the location and the financial incentives in the location.



Electricity generation costs of pure diesel grids

- Costs of local energy production depend highly on the diesel price.
- Subsidization and taxation of diesel have strong effects on costs.
- High diesel prices call for renewable energy sources for electrification.

Image 1: Electricity generation costs of pure diesel grids [1]

In the world the countries seen in red in the map such as Venezuela, Angola or the the MENA countries all possess oil reserves. They have very low domestic diesel prices incentivized for their own population (allowing a price of electricity below 0.1 €/ kWh). Countries not producing oil such as many African and European countries on the contrary have higher prices (starting at 0.3 € / kWh). The most expensive locations are those not having oil and being remote such as Chad, the Amazonas region or Mongolia (reaching more than 1 $ / kWh).

1.1.2 The supply of diesel is unreliable

Lack of resources in islands and geopolitical problems lead to a high unreliability of diesel as an energy source.[2]

1.1.3 Environmental and climate change concerns

Diesel generators emit gases such as particulate matter, CO and high noise that are both disturbing to the senses and dangerous for the health. Oil spills are also very common and difficult to avoid.
Islands are the first affected by climate change due to their very low altitude. This implies that instead of emitting CO2 with diesel gensets, they should be showing the example on the climate change solutions to incentivize the world to follow them.[3]

1.1.4 Green image

Islands often want to attract tourism and increase the life-quality of its inhabitants by getting a "green image" through its energy transformation. This can be seen as not only a useful energy and environmental but also a good economic strategy.

1.1.5 Remote islands

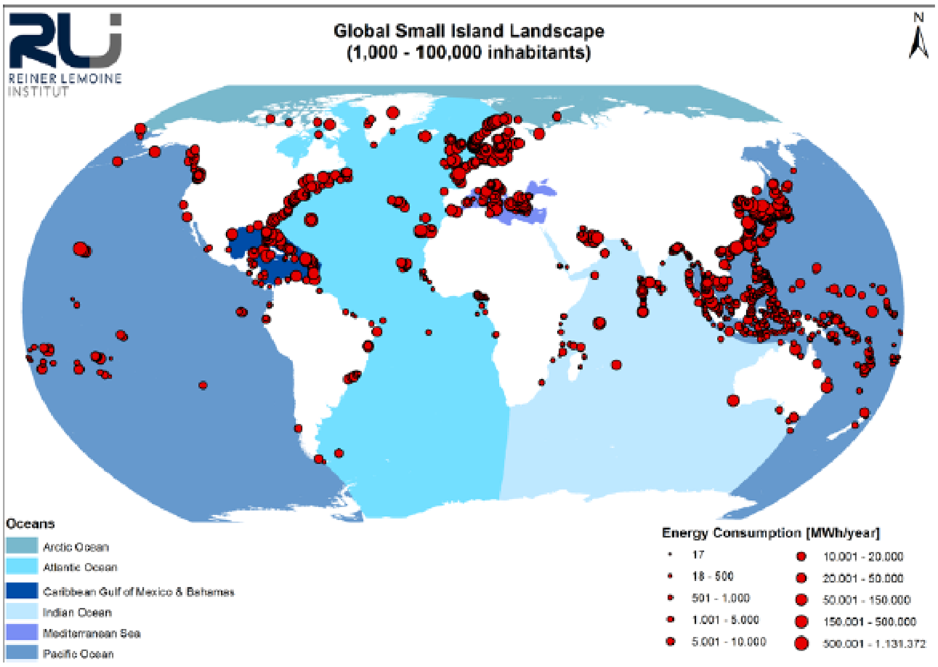
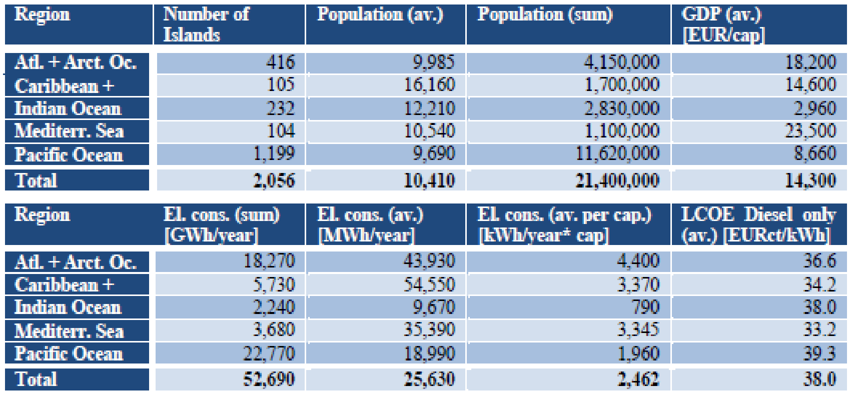


Figure 2: Global map of islands – energy consumption of small islands is highlighted.

Image 2: Global Small Island Landscape [4]

The relevance of this work is appreciated by seeing the high number of islands in the world with a high energy consumption (the big red dots in the map above) and by knowing that the consumption is mostly based on diesel which as seen in the table below yields high costs of electricity (above 0.35 € / kWh).



Region	Number of Islands	Population (av.)	Population (sum)	GDP (av.) [EUR/cap]
Atl. + Arct. Oc.	416	9,985	4,150,000	18,200
Caribbean +	105	16,160	1,700,000	14,600
Indian Ocean	232	12,210	2,830,000	2,960
Mediterr. Sea	104	10,540	1,100,000	23,500
Pacific Ocean	1,199	9,690	11,620,000	8,660
Total	**2,056**	**10,410**	**21,400,000**	**14,300**

Region	El. cons. (sum) [GWh/year]	El. cons. (av.) [MWh/year]	El. cons. (av. per cap.) [kWh/year* cap]	LCOE Diesel only (av.) [EURct/kWh]
Atl. + Arct. Oc.	18,270	43,930	4,400	36.6
Caribbean +	5,730	54,550	3,370	34.2
Indian Ocean	2,240	9,670	790	38.0
Mediterr. Sea	3,680	35,390	3,345	33.2
Pacific Ocean	22,770	18,990	1,960	39.3
Total	**52,690**	**25,630**	**2,462**	**38.0**

Image 3: Islands by region, consumption and LCOE [4]

1.1.6 Existing business case for hybrid systems

The diesel genset market is characterized by a 40 GW of new installed capacity each year. The electricity price from oil (black line) is ever increasing and the PV electricity price (red line) decreasing so that today a business case already exists and the relationship will only become more favorable in the future.

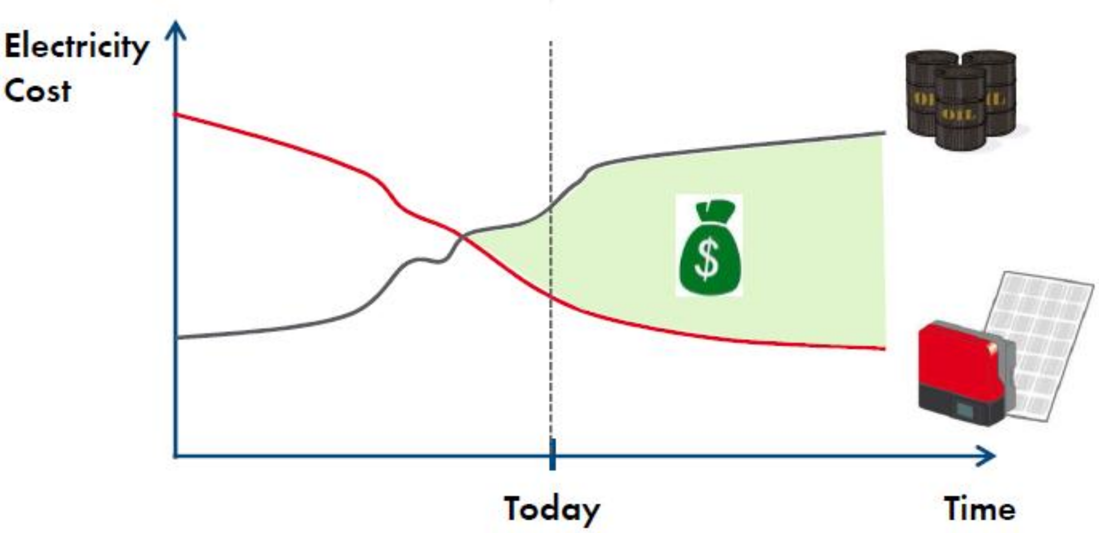
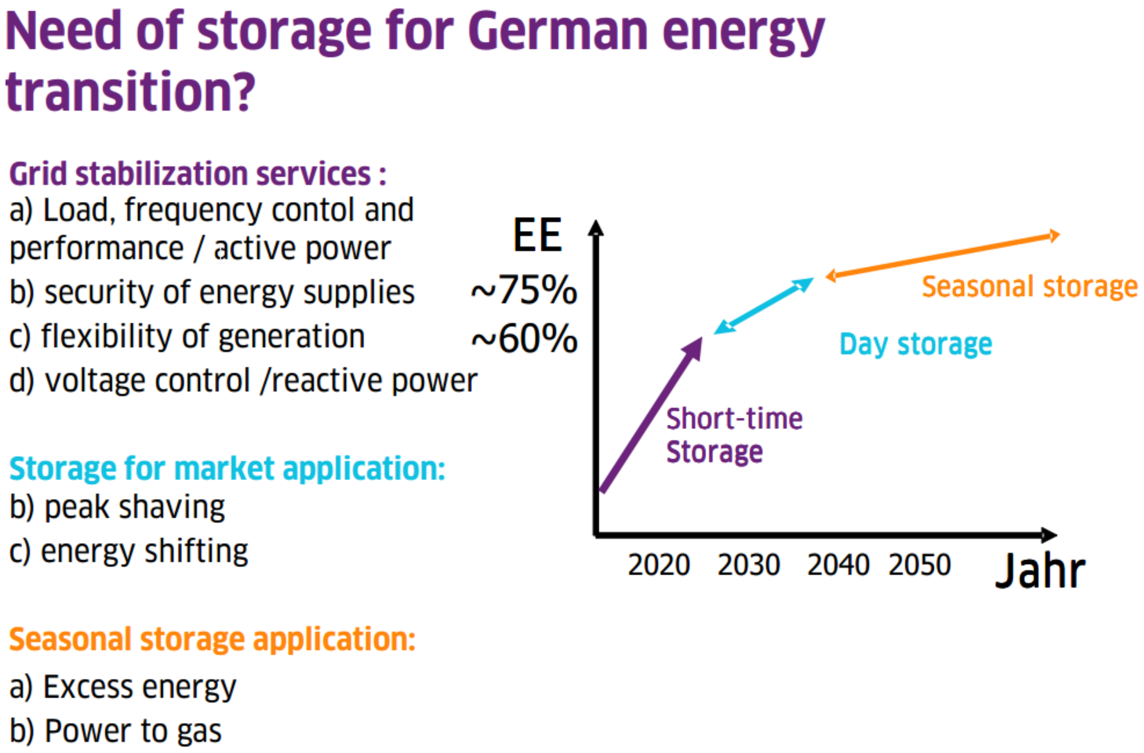


Image 4: Electricity cost vs. time vs. oil and pv cost [5]

1.1.7 Storage needed and becoming viable

First grid stabilization technologies are needed. This allows to reach 60 % of consumed energy penetration. In order to reach higher percentages daily storage and in a final step seasonal storage have to be provided.



Need of storage for German energy transition?

Grid stabilization services :
a) Load, frequency contol and performance / active power
b) security of energy supplies
c) flexibility of generation
d) voltage control /reactive power

Storage for market application:
b) peak shaving
c) energy shifting

Seasonal storage application:
a) Excess energy
b) Power to gas

Image 5: Different storage needs depending on penetration levels [6]

The high costs of storage are mentioned to obstruct the deployment renewables. Through the construction of a lithium ion battery factory that will have a production capacity of 35 GWh / year (doubling the current world's production capacity), the company Tesla Motors wants to reduce the costs of this type of batteries dramatically by 30%. The fact that storage will become a more viable solution makes a high percentage of renewables possible.

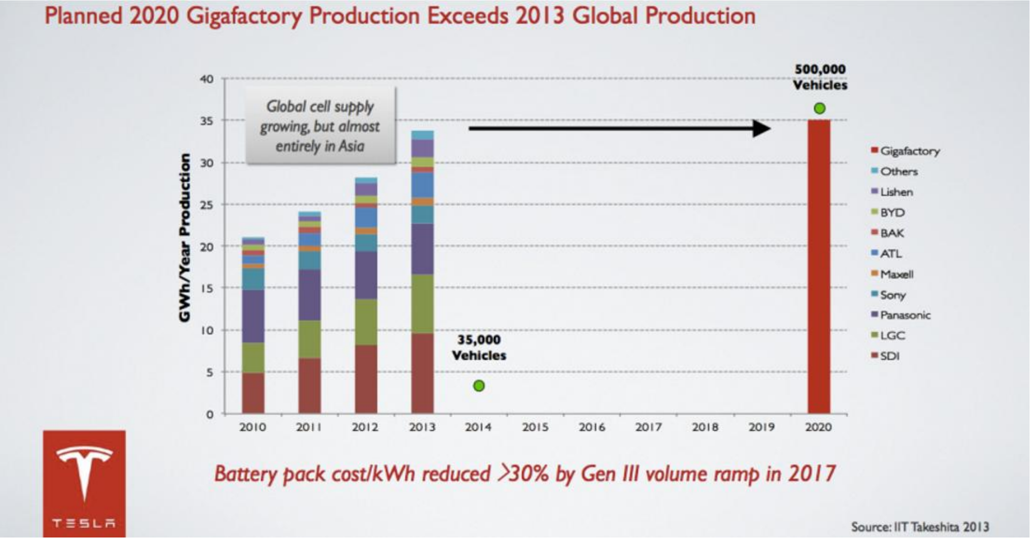


Image 6: Planned lithium ion production of Tesla Motors [7]

According to McKinsey energy storage is one of the 12 disruptive technologies which will change society until 2025. Nowadays, only 3-4 percent of the produced current is being stored. Most of the total 120 GW in form of pumped hydro storage. In 2025, lithium ion batteries will be competitive for storing grid electricity. 1 MWh storage would cost then 85-125 US dollars. Since 2009 did the prices of lithium ion batteries fall by 40 %. [8]

Even though many points are in favour of switching towards a renewable system as fast as possible, many challenges deriving from the intermittency of the renewables still have to be overcome. Systems become more complex, as more components have to function in conjunction. Following a series of definitions, an analysis of these challenges will be made.

1.2 Definitions

1.2.1 Microgrid

Independent or interdependent electricity grid of a main electricity grid, often in a remote location.

1.2.2 kW vs MW

There are many differences between small, below 100 kW, and bigger, MW-scale, microgrids.
small kW systems are often designed to be completely autonomous thanks to renewable energies, with diesel gensets only present as backup. Therefore, batteries,

in most cases of the lead acid type, are indispensable. The autonomy, or days the system can withstand without starting the gensets, vary depending on the designer from 1 to 5.
Bigger systems have not necessarily such a large amount of batteries as the investment becomes too high. Often only short term frequency and voltage fluctuations compensation devices could be installed. Storage for longer periods involves more advanced or even a combination of technologies. A techno-economic optimization of the storage has to be done.

For the kW range, rural electrification projects are the most common. They power a small number of lights, refrigerators and computers of few households or small businesses.
For MW systems bigger technology system providers, like GE and *ABB*, and energy storage solution providers get involved and the load could come from industries, companies and a large number of households. [9]

1.2.3 Grid needs

There are several needs of the electrical grid, each with its own nomenclature.

Frequency regulation
Algorithms quickly and easily respond to grid signals to maintain a stable frequency.

Peak shaving
Literally cut the peak demand by displacing the load towards another time or delivering renewable power when there is a peak in demand.
Spinning reserve
It is the surplus generation capacity that has to be available in seconds in the case of a shortfall of other generation capacities.
[page 55 Energy Storage Systems: Batteries]

Load leveling
Store energy when demand is low and supply energy when it is high.

[10]

1.2.4 Penetration levels of renewable energies

It is of uttermost importance to distinguish between the different penetration level definitions, because they are often used as parameter of comparison which leads to confusions.

The **instantaneous renewable penetration** measures the ratio of renewable power to the system load at any given instant. It varies from moment to moment as the renewable resource varies.
The **peak instantaneous penetration** is the highest level that the instantaneous penetration ever reaches, typically in the middle of a windy night or at noon when the sun is the strongest. It is the relevant measure for much of the integration analysis that

looks at the effect renewable power has on power quality and system stability of the overall electric utility system.

The **energy penetration** or ratio of the renewable power system's energy output to the total energy production of the electric system results in the smallest penetration value for a particular system. [11]

Very low penetration:

It is a hybrid power system, the solar or wind contribution has no effect on the rest of the power system. There is no control mechanism to adapt to the intermittent renewable sources. Their introduced variability is on the same order as the one of the load.

Low penetration:

Renewable energy curtailing and simple controls are necessary at this stage to maintain power quality and enforce the minimum load and ramp rate constraints of the conventional fossil generators in the system.

Medium penetration

These systems able to create a stable grid without the rotating mass of a conventional fossil generator and achieve O&M savings by reducing the run-time of one or more of the conventional fossil generators that can be used only as a backup.

Typical ways to accommodate this are through storage, load management, a large amount of excess renewable output, or some combination of these approaches.

High penetration

Similar to the medium penetration systems but with a larger battery capacity allowing for even higher penetration levels.

100% renewable energies

No fossil generator is present in the system. [12]

The problem with reaching 100 % renewable system is the exponentially increasing higher cost. The hockey stick graph below picturing the LCOE vs. the renewable energy penetration visualized this fact. The price first decreases and starting at 80 % the cost begin to rise dramatically.

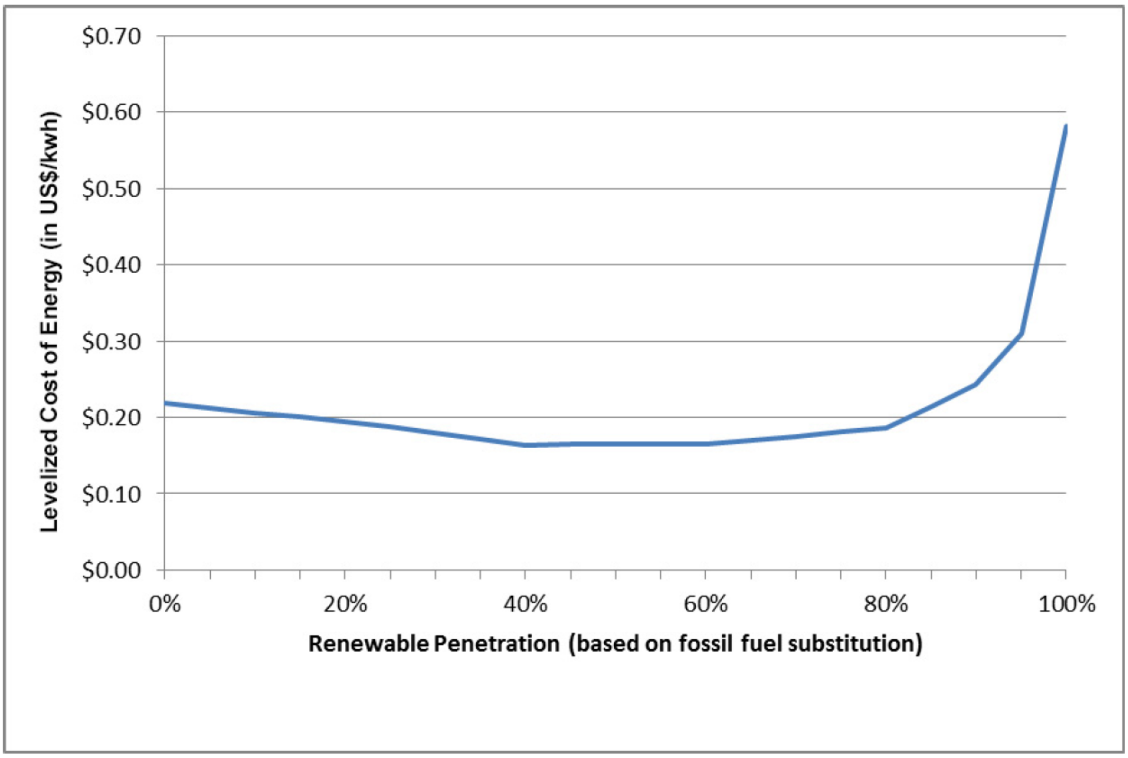
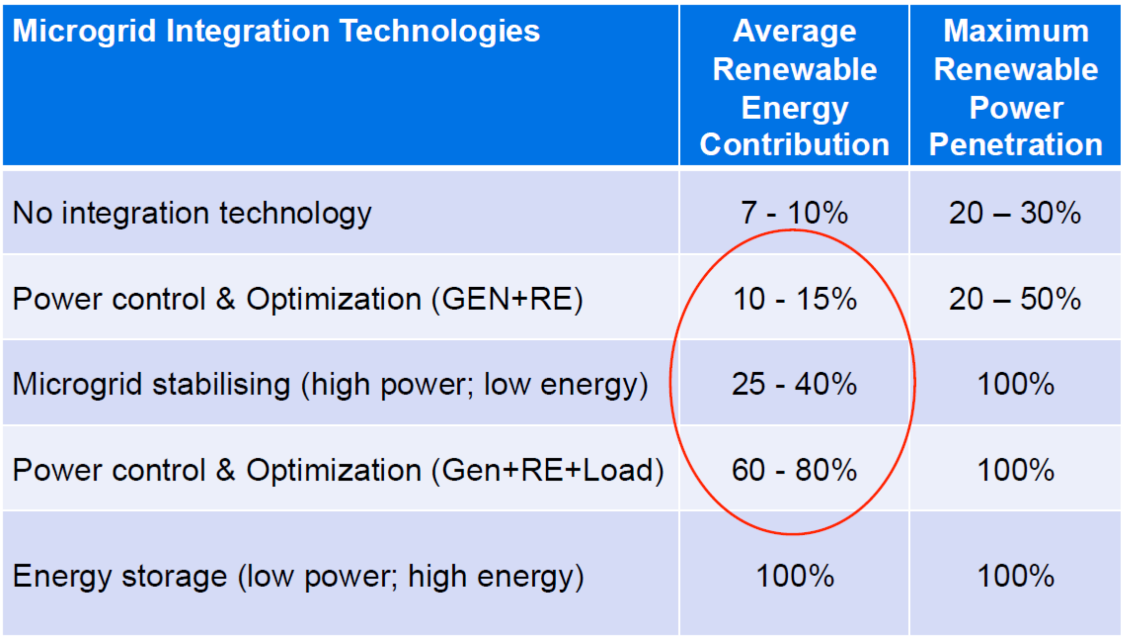


Image 7: LCOE vs. Renewable penetration level [13]

The intermittent nature of the renewable energies leads to a major discrepancy between the share of the renewable energies in the instantaneous power and the annual energy consumption of a microgrid. For instance, when using a microgrid stabilizing technology a power penetration of 100 % can already be achieved but the energy penetration does not exceed 40 %.



Microgrid Integration Technologies	Average Renewable Energy Contribution	Maximum Renewable Power Penetration
No integration technology	7 - 10%	20 – 30%
Power control & Optimization (GEN+RE)	10 - 15%	20 – 50%
Microgrid stabilising (high power; low energy)	25 - 40%	100%
Power control & Optimization (Gen+RE+Load)	60 - 80%	100%
Energy storage (low power; high energy)	100%	100%

Image 8: Renewable energy and power contribution of Microgrid integration technologies [10]

1.3 Scope of the work

After this introduction a benchmarking of the MW-scale technologies for microgrids will yield a good understanding of relevant solutions to be considered for island locations.

Due to the limited scale of this thesis only the most common and promising technologies for microgrids are analysed more in detail. The most relevant players in the market are shown. It has to be stressed that possible omissions are due to time limitations.

In a next step, in order to get an overview of the state-of-the-art of the technologies, the electrical situation of islands with an existing or a planned high share of renewables are analysed.

Then, the case study is started showing the status quo of the island first. Afterwards, a pathway towards a large penetration of renewable energies, shown through a techno-economic analysis with the software HOMER, leads to discussion and a potential LCOE and a NPC of the island.

2 Benchmarking of MW-scale technologies for microgrids

This part will be a study of the technical particularities of the different technologies. Each technology's advantage, disadvantage and main challenge to be overcome will be pointed out. The different players in the market will be presented.

2.1 Energy Generation

As mentioned before other microgrid technologies such as OTEC, geothermal, biomass, solar thermal, run-of-the-river hydropower etc. could not be looked into due to the limited time. They are and/or could become relevant candidates in the future. [14]
The manufacturers of each generation technology will not be shown as the focus of the work lies more in the stabilization and storage aspect.

2.1.1 Solar photovoltaic (PV)

Per definition PV modules are modular and easy to transport in containers.
The resource is predictable with available data of NASA satellites for the yearly and monthly average. For the daily and hourly variation the behaviour is more unpredictable due to clouds but a daily forecast is often possible.
A high CAPEX is necessary.[15]

2.1.2 Wind Power

As most of the assembly of the wind turbines is done in a plant far away from the installation's location the transport of big wind turbines results difficult. The resource is available from NASA but is less predictable than the sun. A high CAPEX is necessary but the LCOE is generally low. The capacity factor is often higher than PV. [15]

2.1.3 Diesel gensets

Diesel gensets claim a high OPEX but low CAPEX.
They possess no grid stabilization problems and can undergo a variation between base load, peak load and standby only causing efficiency losses.
There is an efficiency discrepancy between generators of different power. As seen comparing the genset 100 kW prime and the genset 30 kW, not only does the higher power make the genset more efficient, the efficiency curve is different as well, the lower the power the more linear the curve. Also bigger generators seem to be able to achieve lower load ratios of down to 10 %.[15]

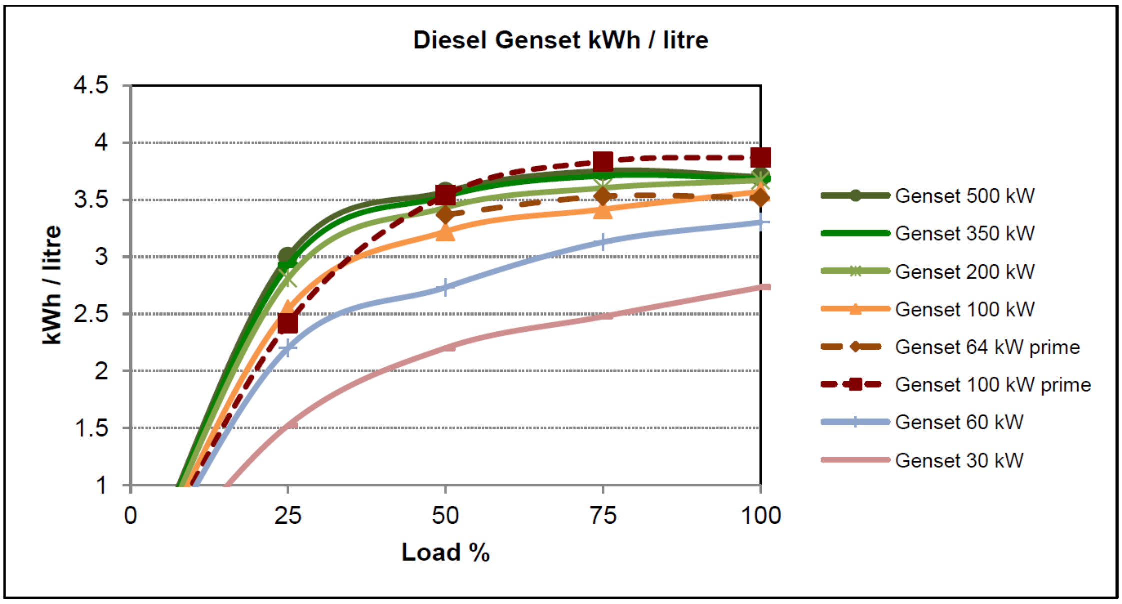


Image 9: 30-500 kW Diesel Gensets: kWh/l production for different loads [16]

2.2 *Energy conversion & flow management:*

2.2.1 Converters

Inverters are used to convert the photovoltaics' DC current into AC current. They are also often used to control the energy flow.

There are different types of inverters :

Grid forming allowing for a virtual power plant: This means that it can form a grid (with a frequency and voltage) without the need of a diesel genset or a national grid.
Example: *Princeton power system's* inverter simulates an AC generator by providing grid-forming capability, frequency and voltage change adaptability.

Isolated: The inverter is either only used in a small system (e.g. house) or is connected to a small microgrid. They often require grid forming capability.
Example: small inverters of *Victron Energy* or *Studer*.

Battery/bidirectional inverter: A bidirectional inverter (inverter and rectifier in one device) used for batteries.
Example: Sunny Island. *SMA solar technology AG (short SMA)* does still not offer a grid forming inverter above 300 kW.

Grid-connected: The inverter is connected to a national grid.

1 or 3 phase: Depending on the application's power range and consumption a 1 phase inverter for low ranges or a 3 phase inverter for larger ranges are used.

String: This inverter is used to connect a string of solar modules.
Example: The grid-connected Sunny Boy for 1 phase or Sunny Tripower for a 3 phase

system of *SMA*.

Centralized: Similar to string inverters but bigger power starting at 500 kVA.
Example: *SMA* sunny central.

2.2.2 Turnkey solutions

Other necessary equipment for the converter system used in energy storage systems (ESS) are AC or DC switchgear for grid connection, transformers, DC/DC converters, sine filters, closed loop control of AC voltage and frequency and synchronizing with the grid.

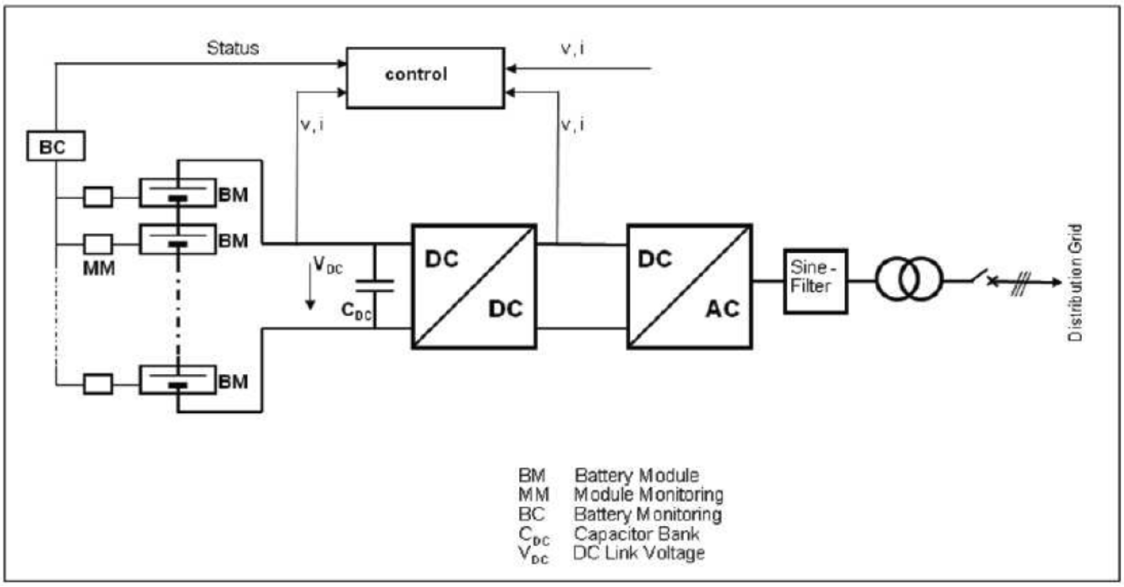
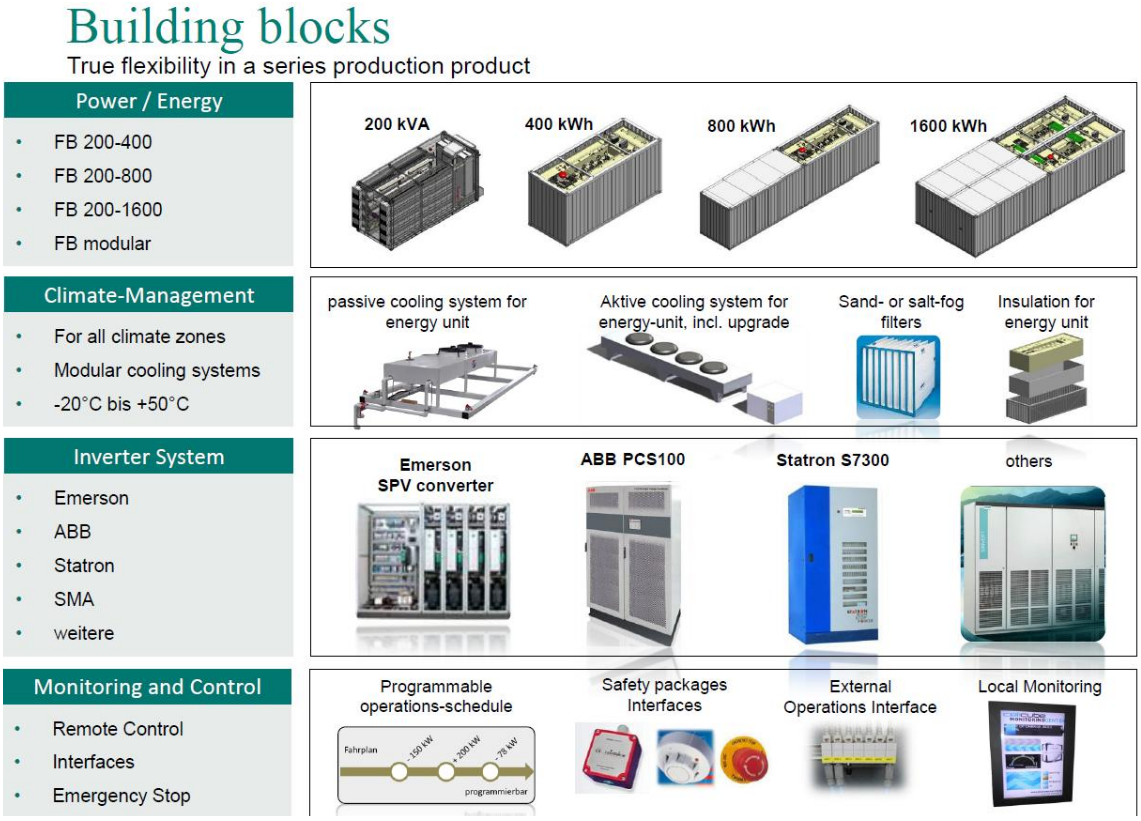


Image 10: Woodward's energy storage system components [17]

There are all in-one solutions in the market that combine storage and inverter(s).
The *Cellcube* of *Gildemeister* for instance combines the Vanadium redox flow batteries (VRB) with inverters of varying providers.



Building blocks

True flexibility in a series production product

Power / Energy

- FB 200-400
- FB 200-800
- FB 200-1600
- FB modular

200 kVA
400 kWh
800 kWh
1600 kWh

Climate-Management

- For all climate zones
- Modular cooling systems
- -20°C bis +50°C

passive cooling system for energy unit
Aktive cooling system for energy-unit, incl. upgrade
Sand- or salt-fog filters
Insulation for energy unit

Inverter System

- Emerson
- ABB
- Statron
- SMA
- weitere

Emerson SPV converter
ABB PCS100
Statron S7300
others

Monitoring and Control

- Remote Control
- Interfaces
- Emergency Stop

Programmable operations-schedule
Safety packages Interfaces
External Operations Interface
Local Monitoring

Image 11: Gildemeister's Cellcube configuration [18]

2.2.3 Energy flow management

Multiple inverters control

The control strategies of a microgrid can include many different components.
In the multi-master inverter-dominated architecture several generating sources control the frequency and the voltage. These sources (e.g. batteries) are either interfaced to the grid by inverters or in form of diesel gensets. The inverters can be in master-slave mode which is characterized by one inverter regulating the frequency and voltage and the other inverters following the values. Through modern communication methods the parallel operation of multiple grid-forming inverters is made possible.[19]

The company *Younicos* develops control systems for the combination of renewable energy generation and different storage systems. Its control system integrates the BMS of battery manufacturers and optimizes the conjunctions of different batteries with the grid-forming inverters. This prolongs the battery life, optimizes the grid needs and the economics of the system. [20]
The grid needs include frequency and voltage regulation, power control, black start capability and the supply of short circuit power. According to *Younicos* "*The inverters work in parallel: several grid-forming inverters operate with no additional communication structures required. They „inform each other“ solely via the grid frequency. This is unique in Megawatt-scale power grids.*" [21]
The control is achieved via communication through an IEC protocol.

Fuel save system controllers

The fuel save controller is used to add PV into a diesel microgrid in order to save fuel. The particularity is that it is able to measure the different instantaneous power values of each component and communicate it to other components in order to regulate the power flow continuously. It allows to obtain up to 25% renewable energy share for the yearly consumption.

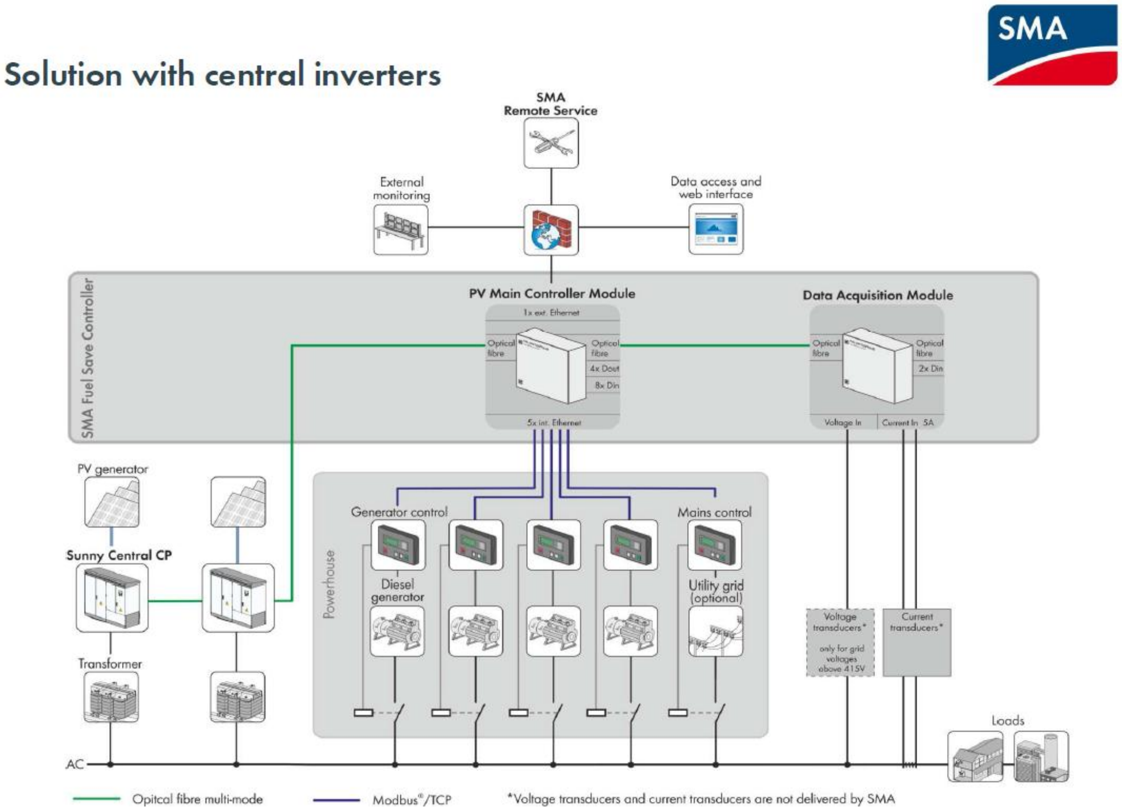


Image 12: *SMA*'s fuel save controller configuration [22]

The picture above shows the *SMA* solar fuel save solution. It is composed of a series of data acquisition modules measuring voltage and current and guaranteeing through an algorithm that each component respect pre-established grid limits.
The main Fuel saver providing companies are *SMA*, *DHybrid*, *Kaco New Energy* etc.

ABB's product is the controller *Microgrid Plus System* which is more flexible than a typical fuel save controller as it can include also other components such as wind turbines. It is more costly though as it has to be newly developed for different projects.
The flexibility can be seen in the two images below. In the first, all the configurable parameters depending on the control module are pictured. All of them can provided power station black start but only a few support an overload.

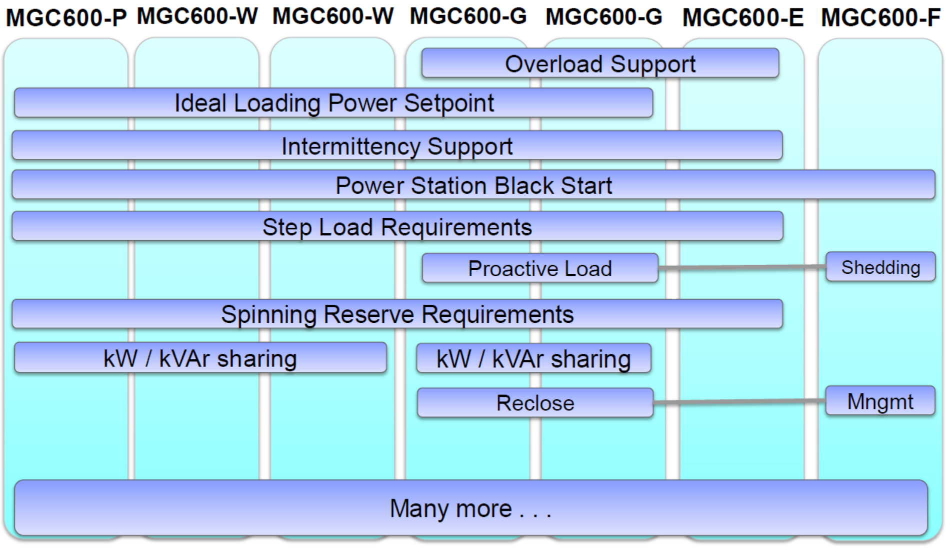


Image 13: ABB's Microgrid Plus System's abilities per controller [23]

The diagram below explains the power flow management in which all controllers (of wind turbines, PV plants, diesel gensets etc.) named with different letters communicate with each other through a communication network.

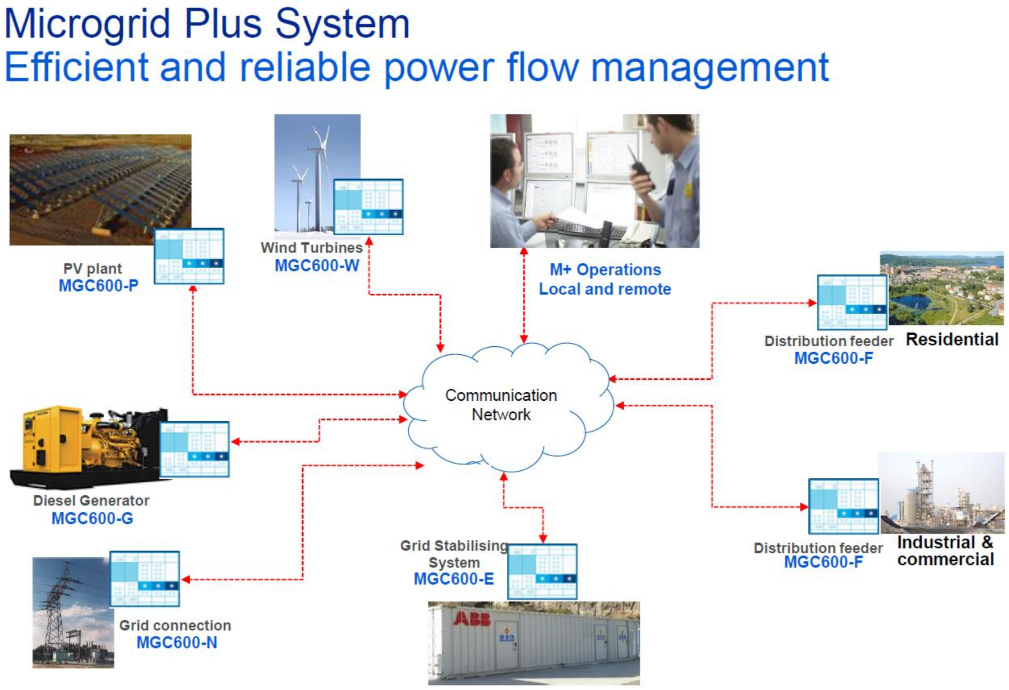


Image 14: Microgrid Plus System's communication network of controllers [23]

Constraints for the energy control

Most generators cannot work below 30 % of their nominal power without being damaged due to wet stacking (accumulation of particles caused by incomplete combustion), carboning, fuel dilution etc.. This 30 % corresponds to the minimum load ratio. p40 of [19]

The spinning reserve of the generators has to equalize the renewable energy power. Hence, more than a certain percentage of intermittent renewables cannot be reached without storage due to the unstoppable rotating mass of the diesel gensets

2.3 Short term grid stabilization

The short term grid stabilization is defined in terms of time which is very short term storage in the range of ms, s, minutes.

The total efficiency (meaning a cycle consisting of one charge and one discharge) of each technology is very different. As it can be seen the supercapacitors (90%) are the most efficient followed by lithium ion batteries (86%), flywheels (81%), lead acid batteries (77%) and at the end hydrogen (32 % for the gaseous one). This explains why certain technologies are used for the very frequently occurring shot term storage where as others are only used for the long term storage.

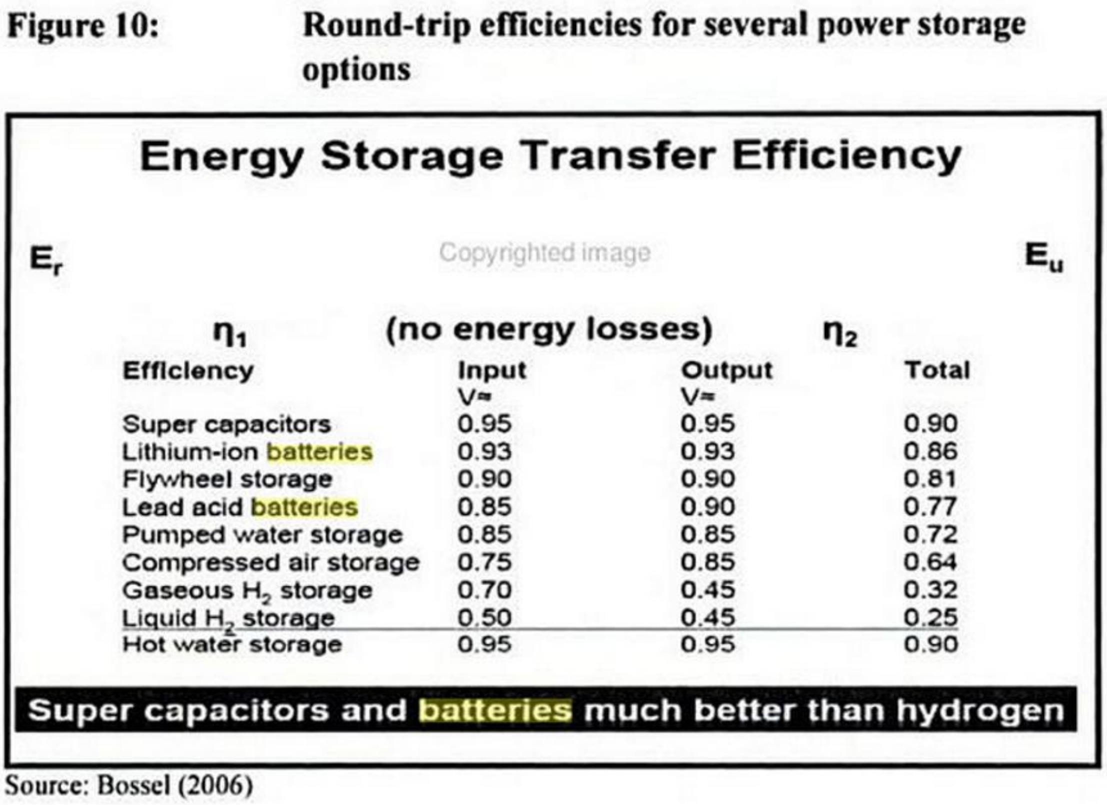


Figure 10: **Round-trip efficiencies for several power storage options**

Energy Storage Transfer Efficiency

E_r E_u

η_1 (no energy losses) η_2

Efficiency	Input V=	Output V=	Total
Super capacitors	0.95	0.95	0.90
Lithium-ion batteries	0.93	0.93	0.86
Flywheel storage	0.90	0.90	0.81
Lead acid batteries	0.85	0.90	0.77
Pumped water storage	0.85	0.85	0.72
Compressed air storage	0.75	0.85	0.64
Gaseous H_2 storage	0.70	0.45	0.32
Liquid H_2 storage	0.50	0.45	0.25
Hot water storage	0.95	0.95	0.90

Super capacitors and batteries much better than hydrogen

Source: Bossel (2006)

Image 15: Energy storage transfer efficiency depending on technology [24]

2.3.1 Flywheels

Concept

The technology is very old. However it has evolved technologically very recently including components such as carbon-fiber composite materials, advanced semiconductors and other electronics, hybrid magnetic bearings, and motor-generator designs that allow for extremely fast response to control signals with high efficiency. [25]

Flywheels present many advantages such as a high efficiency of around 90-95%, a huge variety of power levels with rapid charge and discharge rates and a good recyclability. Nevertheless, the short storage time of often only up to 30 seconds for the ones that are already commercially available, the high upfront cost and the rather significant self discharge of 0.18-2 times the stored capacity per hour are important disadvantages. One other essential aspect of the flywheel is that it cannot be shaped in any specification as it can be nearly achieved with batteries. The size is inflexible that means it can be ramped up in a specific power step only.[26]

As can be seen below the *Powerstore* combines a flywheel, flywheel inverter, a virtual generator and a transformer that allow to exchange real and reactive power with a grid.

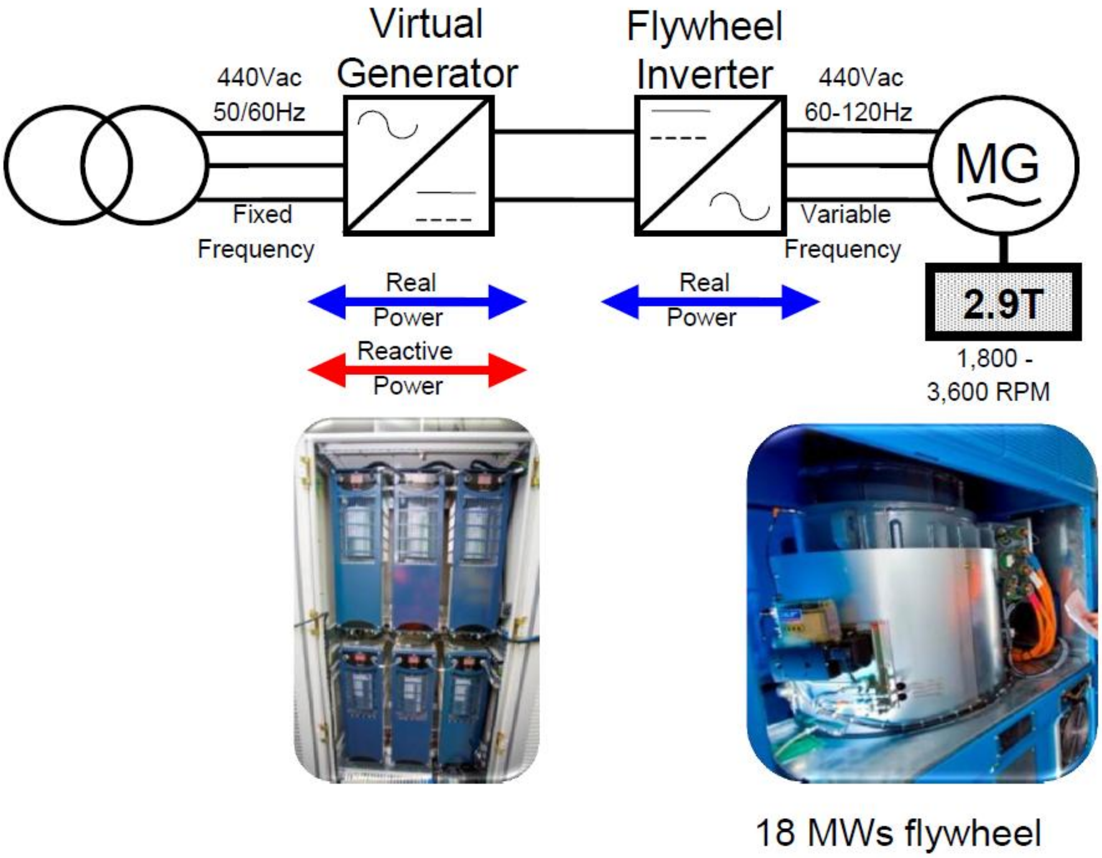


Image 16: Powerstore additional components [27]

The detailed representation of the *Powerstore*'s design with fixed sizes for bearings, excitation generator, flywheel, magnetic support etc. emphasizes the difficulty in changing power or capacity of the device, as all the design should change.

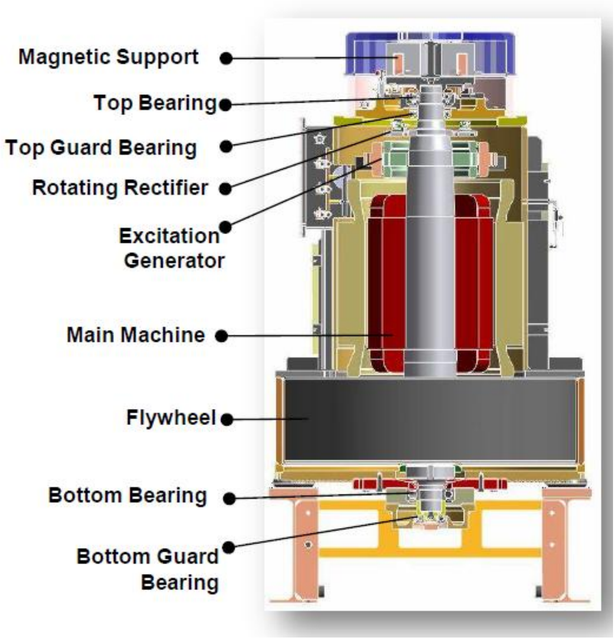


Image 17: Powerstore detailed design [27]

The variation in the graph below represents the frequency output of a wind turbine-diesel system with (variation between 49.5 and 50.5 Hz) and without (variation between 48 and 51 Hz) a *Powerstore* compensation. The benefit of adding a flywheel for a more stable frequency becomes clear.

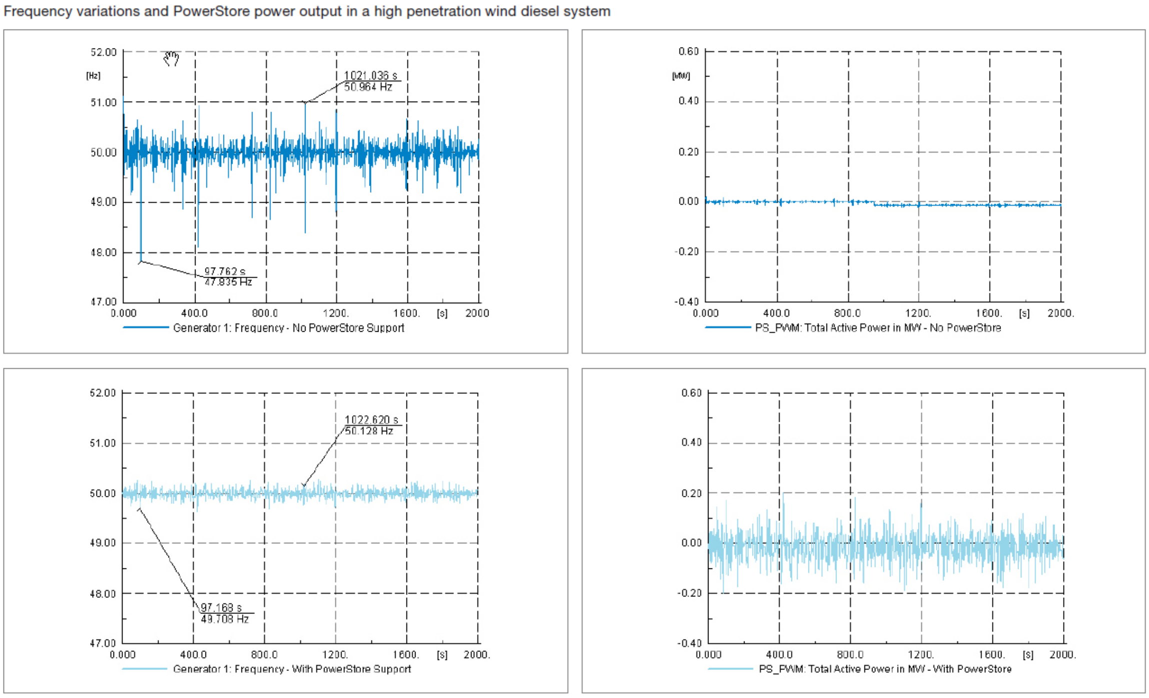


Image 18: Frequency variations and Powersore output in a high penetration wind diesel system [27]

The flywheel provides spinning reserve, so it reduces or eliminates the need for the diesel plant to provide it. That should allow the diesel plant to operate fewer or small generators, saving diesel fuel and O&M expenses. It uses the frequency and voltage to regulate the absorbed and delivered power.

Examples

All the examples with a *Powerstore* need to go along with a *Microgrid Plus System*.

A 70 % wind power peak penetration was achieved by *ABB* in the wind turbine-diesel-flywheel system of Ross island, Antarctica. A 9*125 kW of diesel gensets were complemented by a 3*330 kW wind power plant and a 500 kW *Powerstore*.[28]

A 100 % wind peak power was achieved by *ABB* thanks to the flywheel in Flores composed of hydro (3x250 kW + 600 kW), wind (2x300 kW), diesel generators (3x500 kW + 810 kW) and a peak power around 2 MW. [28][29]

The Marble bar system of *ABB* in Australia is one of the rare PV-diesel-flywheel examples. In the solar irradiation graph of Marble Bar for a few days represented below, the need for a compensation device becomes obvious. Especially, looking at the second day where clouds cover the output very frequently.

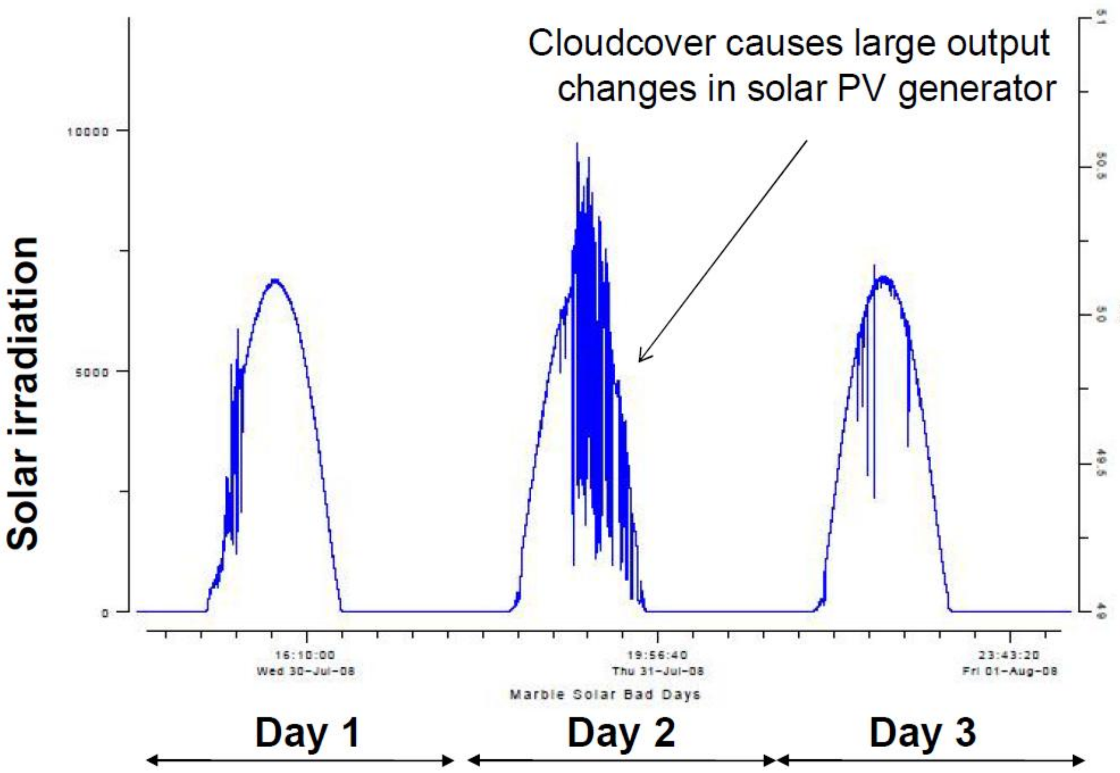


Image 19: Solar irradiation during different days [30]

Kodiak Island with 15,000 people in Alaska has a system that consists of 19 MW of hydro power, 9 MW of wind power, a 2 MW flywheels and 1.5 MW battery system similar to the system in El Hierro seen later on allowing for a high penetration of renewables. [31]

In Stephentown the grid-tied system composed of 200 units of Beacon Power SE 25, with a nominal capacity of 25 kWh each, absorbs and delivers power for 15 min, with a power of 14 MW. [25]

Companies: *Beacon Power, ABB*

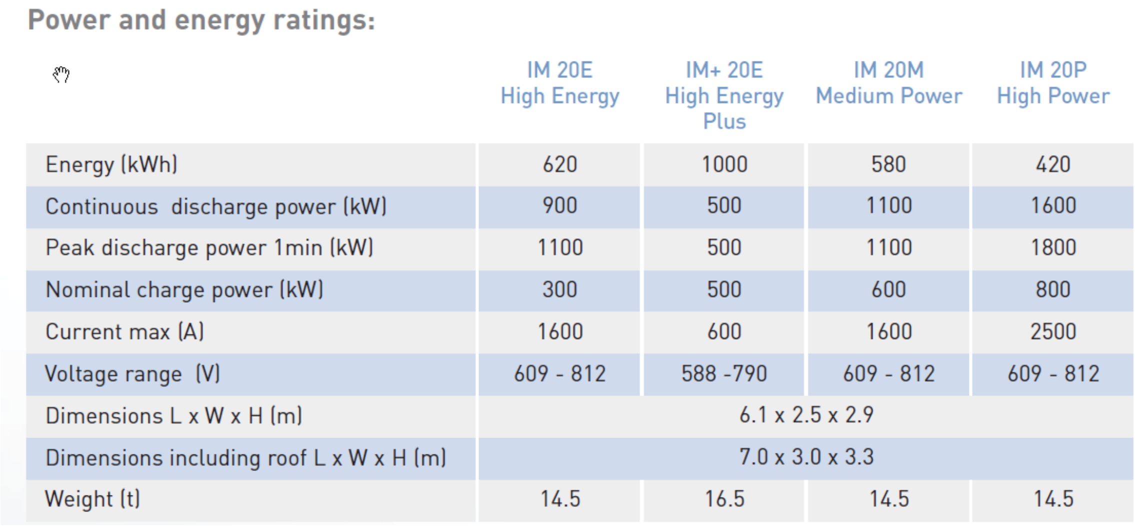
2.3.2 Batteries

Concept

Batteries can also be used for short time grid stabilization purposes. Some battery chemistries are more adapted than others especially thanks to their superior reaction time and slower degradation.

Generally, the bigger the energy needed, the less the power capability depending on the chemistry. For instance, the lithium cobalt type has a high capacity and the lithium manganese type has a lower capacity but higher power and long life. [32]

The Energy storage system of *SAFT* as seen below with the *Intensium Max 20 (IM)* shows the difference in power and energy ratings depending on different lithium ion chemistries.



Power and energy ratings:

	IM 20E High Energy	IM+ 20E High Energy Plus	IM 20M Medium Power	IM 20P High Power
Energy (kWh)	620	1000	580	420
Continuous discharge power (kW)	900	500	1100	1600
Peak discharge power 1min (kW)	1100	500	1100	1800
Nominal charge power (kW)	300	500	600	800
Current max (A)	1600	600	1600	2500
Voltage range (V)	609 - 812	588 -790	609 - 812	609 - 812
Dimensions L x W x H (m)	6.1 x 2.5 x 2.9			
Dimensions including roof L x W x H (m)	7.0 x 3.0 x 3.3			
Weight (t)	14.5	16.5	14.5	14.5

Image 20: *SAFT's Intensium* product range's power and energy ratings [33]

Examples

There are very few examples of battery grid stabilization applications in microgrids.

ESS pro *ABB* world's most powerful battery achieved 46 MW for 5 minutes in Alaska. It is used as spinning reserve. [34]

A 200 kWp PV plant in Kei Besar island has been equipped with a 240 kW ESSPro power conversion system and batteries that aims at controlling the battery charging and discharging. It has the ability of working when the grid power is being provided and when it is unavailable. During off-grid times it acts as a grid forming inverter. [35]

The 1.2 MW PV plant in Tudela was combined with 1 MW and 560 kWh *Intensium Max* 20 energy storage system of *SAFT*. It is used to regulate the power fluctuations of the plant and provide primary regulation. Another project example is Gran Canaria where a *SAFT Intensium Max* 20 with 1 MW of power and 3 MWh of capacity has been installed to help smooth the peak demand.[36]

Metlakatla Power and Light (MP&L) has an ESS installation consisting of VRLA cells of the company Exide, providing rapid spinning reserve, frequency control, and better power quality. Beginning operation in 1997, the ESS has a 1 MW peak power output, and 1.4 MWh energy capacity. It is capable of supporting continuous loads of 800 kilovolt amperes (kVA) and pulse loads up to 1200 kVA.
In the USA, *Axion Power* has implemented a project for frequency regulation with its PbC product called *PowerCube* for the utility PJC. Each of the batteries is tied to solar arrays that produce between 500 kW and 700 kW of power and the batteries will each provide 500 kW. [37]

Duke Energy matched a $22 million grant from the U.S. Department of Energy to install an ESS capable of storing electricity produced by their 153 MW Notrees wind farm. *Xtreme Power* designed, installed and operate the largest battery storage system in the world integrated with a wind farm.
System size: 36 MW/ 9 MWh advanced lead acid storage, 15 minute duration
Applications: Ramp Control, Frequency Response, Voltage Support.[38]

Companies for lithium ion batteries: *SAFT*, *ABB* etc.
Companies for lead acid batteries: *Axion Power*, *Xtreme Power*, Exide

2.3.3 Ultracapacitors

The ultracapacitors/supercapacitors are a promising technology as they have a large amount of cycles (up to 1,000,000) and high efficiency (95%). They are not analysed further as they are still mainly in development phase. No references of implemented commercial projected have been found.
[39][40]

A reference found is a research project with a 4MW/6s supercapacitor, commissioned in 2013 in La Palma (Spain), for minimizing the loss of generation capacity and avoiding blackouts.

Main manufacturer: *Maxwell technologies*.

2.4 Energy Storage

The energy storage corresponds to a short to long term storage in the range of hours to days.

Due to the limited scope only some main technologies are displayed. It has to be mentioned that many other relevant technologies exist. Especially, the pumped hydro storage being the most common one will be left aside as it is not applicable to every location due to its need of an elevation.

Storage solutions can be thermal, electrochemical, chemical, electrical and mechanical. Previously, the mechanical type in form of flywheels, electrical in form of capacitors and the classic batteries in form of lithium ion batteries have already been introduced for grid stabilization purposes. In this chapter, there will be a special focus on the electrochemical type and a brief part about the hydrogen storage.

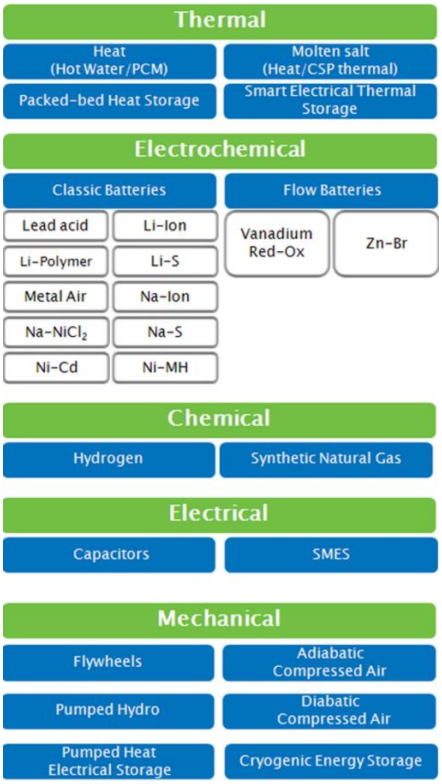


Image 21: Storage technologies[41]

As seen in the graph below, storage technologies can be subdivided into power ratings, function and discharge time categories. Most of the electrochemical solutions are used for UPS (uninterruptible power systems used for transition periods when a generator is shut down) and grid support for power ratings up to 10 MW starting at minutes and reaching the hours. The pumped hydro and the supercapacitors oppose each other for example. The first one being used for energy management at high power ratings above 100 MW and for hours. The second used for UPS and grid support for power ratings up to 1 MW and only seconds. Flywheels are right in between with grid support features of the high kW to low MW range for minutes.

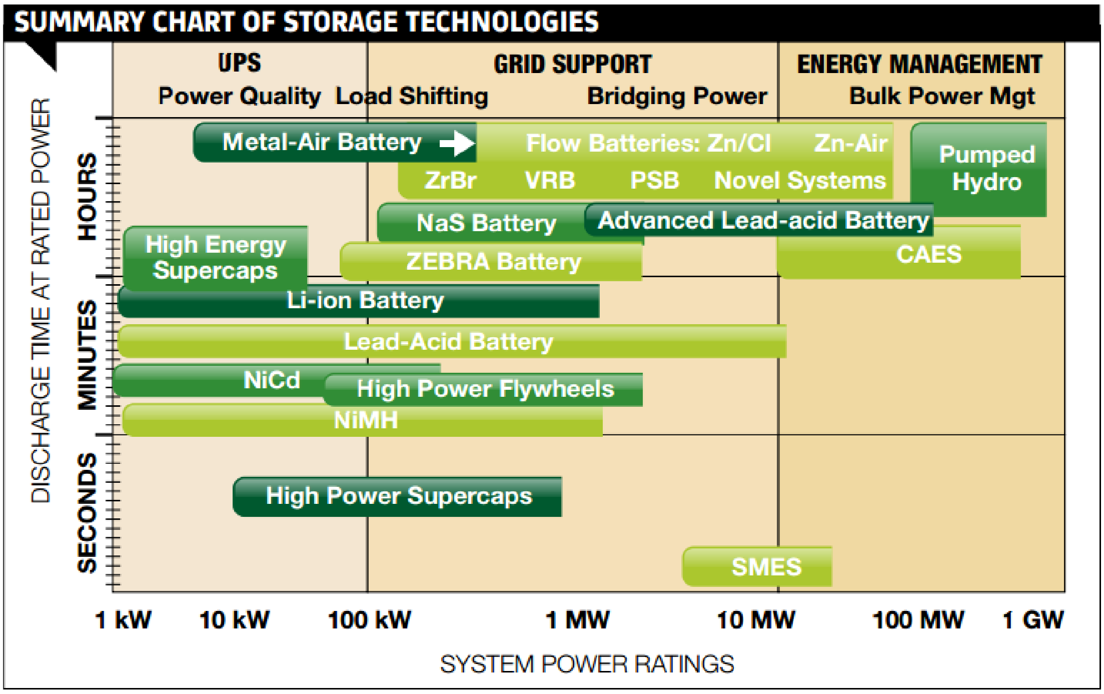


Image 22: Graph stabilization per storage depending on time[42]

2.4.1 Batteries

The batteries are especially distinguished depending on their power to energy ratio. Lithium ion and lead acid batteries possessing better power characteristics and Redox flow and high temperatures rather excelling at long term energy storage.

Image 23: Battery technologies differentiated between power and energy [43]

2.4.1.1 *Lead acid/advanced lead acid*

This is the most widely used type of electrochemical battery especially for remote areas.

It is composed of lead dioxide as the active material of the positive electrode, metallic lead, in a high-surface-area porous structure, as the negative active material and a sulphuric acid solution.

Several sub-technologies can be distinguished by the electrolyte which is either flooded, immobilized by a gel or an absorptive glass mat.[32]

They present a short lifetime of an average of 5 years depending on usage i.e. high discharge currents, high depth of discharge (DOD), hot environment. But thanks to the above mentioned composition they have a low cost of investment of around 250 $ / kWh. The energy density is low. The total efficiency lies at a maximum of 80 %. Its power-energy relationship is 1:6. [44]

Advanced lead acid or PbC batteries are structured like conventional lead acid batteries with the difference of added carbon at one electrode that reduces corrosion. This increases they lifetime and performance.

Respectively the biggest lead acid battery manufacturer is *Hoppecke* and the biggest PbC manufacturer is *Axion Power.*

2.4.1.2 Lithium ion

The lithium ion family of batteries promises a substantial cost reduction and its field is very dynamic as shown in the introduction.

The power-energy relationship varies depending on the chemistry as it has been defined in the previous chapter.

It has a total high efficiency of around 85%-95% and costs varying from 350-1000 $ / kWh.[39]

The anode is made of carbon, while the cathode is a lithiated metal oxide (LiCoO2, LiMO2, etc.). The electrolyte is made up of lithium salts (such as LiPF6) dissolved in organic carbonates.[32]

During the charging step, lithium ions dissociate from the lithium metal oxide electrode to join the graphite electrode. When the discharging occurs the opposite flow is taking place.

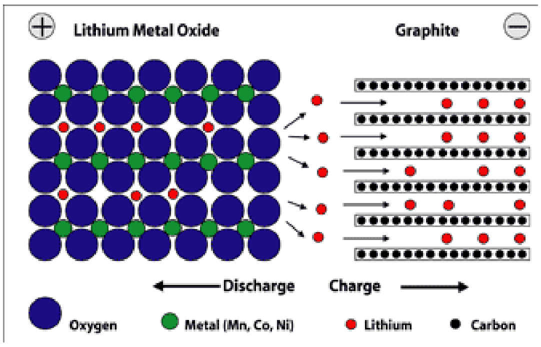


Image 24: Lithium ion batteries working mode [32]

Thanks to the high capacity of active materials and a single cell voltage of 3.6 V, it provides the highest energy density of all rechargeable systems operating at room

temperature.
Often battery manufacturers become ESS providers. As examples, *SAFT* and *BYD* manufacturer batteries and provide the complete ESS. *Siemens*, *Autarsys* and *ABB* are exclusively ESS providers purchasing the battery. Some rare companies only manufacturer batteries.

2.4.1.3 High temperature batteries

These batteries function in a very different way. As two big players in the industry (*GE* and *Younicos*) bet on this technology, it is presented. It is built of earth abundant and inexpensive materials. As the name indicates the operating temperatures are high with 300-350 °C.

These batteries have liquid electrodes and a ceramic solid-state electrolyte. A high temperature is necessary to keep electrodes in a molten state and to achieve a sufficient ion-conductivity in the electrolyte. There is only 2 types, NaS and ZEBRA.
There is practically no side reactions. This is a big advantage because as a consequence they have a high energy efficiency. In addition, these batteries show practically no ageing effects. The disadvantage is the required high operational temperature that through the cooling down and warming-up causes high mechanical stress in the ceramic electrolyte and it can break up.

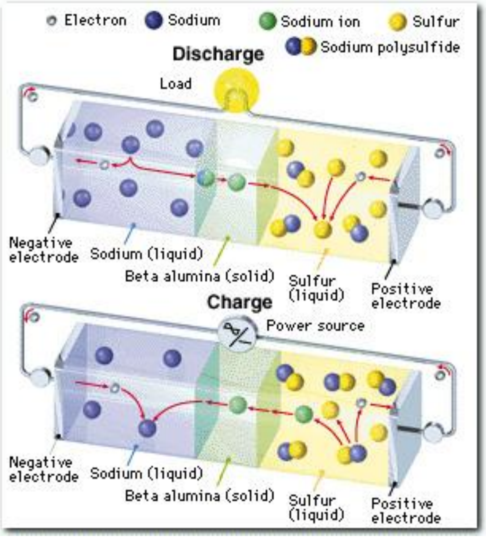


Image 25: NaS batteries working mode [45]

During the discharging, the electrons leave the sodium electrode to reach the sulfur liquid. In the charging process, the reverse cycle occurs.
These batteries are characterized by a long lifetime of 15 years or 4600 cycles. The total efficiency lies at 85%.[46]

NGK is a producer of batteries and GE provides an ESS based on this battery that it manufacturers as well.

2.4.1.4 Redox flow batteries

This typology of batteries has a very different working mode than the classic electrochemical batteries. Many projects have been realized based on this technology which is the reason to analyse it further.
For the flow batteries the power and energy parameters are disconnected. The size of the electrodes defines the power and the exchangeable electrolyte defines the energy. [page 57, Energy Storage Systems: Batteries] [47]

A typical flow battery consists of two tanks of liquids which are pumped past a membrane held between two electrodes. In the case of the *Cellcube*, the energy carrier is Vanadium.

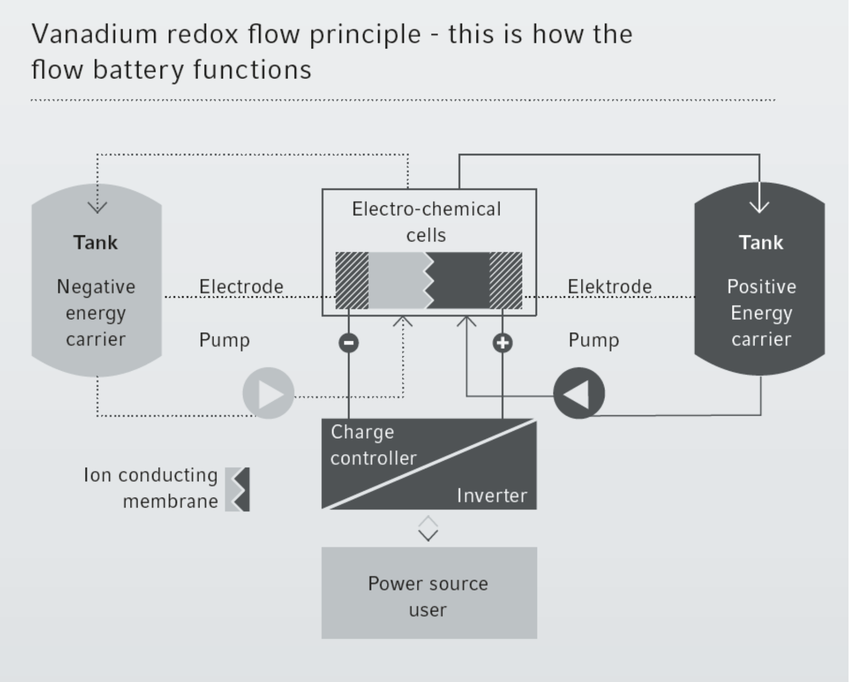


Image 26: Vanadium redox flow principle[18]

The 100 % DOD capability, the unaffected lifetime from different charge and discharge conditions and the practically non-existent self-discharge are the main advantages of this technology. The total efficiency is rather low with 80%. This makes it a good technology for storage for longer periods.

The most well known manufacturers are *Gildemeister*, *Prudent* and *Imergy*.

Gildemeister already installed 60 *Cellcube*s until 2014 in the European and Asian market.
[48]

2.4.1.5 Hybridization

After evaluating 27 storage solutions on durability, reliability, economic viability and future cost reduction *Younicos* decided to focus on a hybrid storage solution composed of Lithium-ion for the short term, NaS for the medium term and VRB that provide the

long term storage. [21]

In the research project M5bat different batteries technologies are used as well. The short term demand is covered with lithium ion batteries, lead acid for one hour or less and high temperature batteries for several hours. [49]

With the *ABB* ESS pro PCS 3 hybrid storage solutions are made possible containing lead acid batteries, flywheel and supercapacitors. [50]

AEG uses lithium ion for power application and lead acid for the longer storage capacity. [51]

The combination of batteries and flywheels can also be an option. The flywheels would be used for the very short term renewable energy variations as they are more robust for frequent changes. The batteries would operate starting at period of several minutes and hours. This expands the lifetime of the batteries.[24]

2.4.2 Hydrogen

According to *Younicos* the economic optimum for energy penetration lies at 88 % for only battery storage. For the final 12 %, 3 different technologies can be considered. Synthetic diesel (used in diesel genset), synthetic gas (used in a gas turbine) and hydrogen (used in a fuel cell).

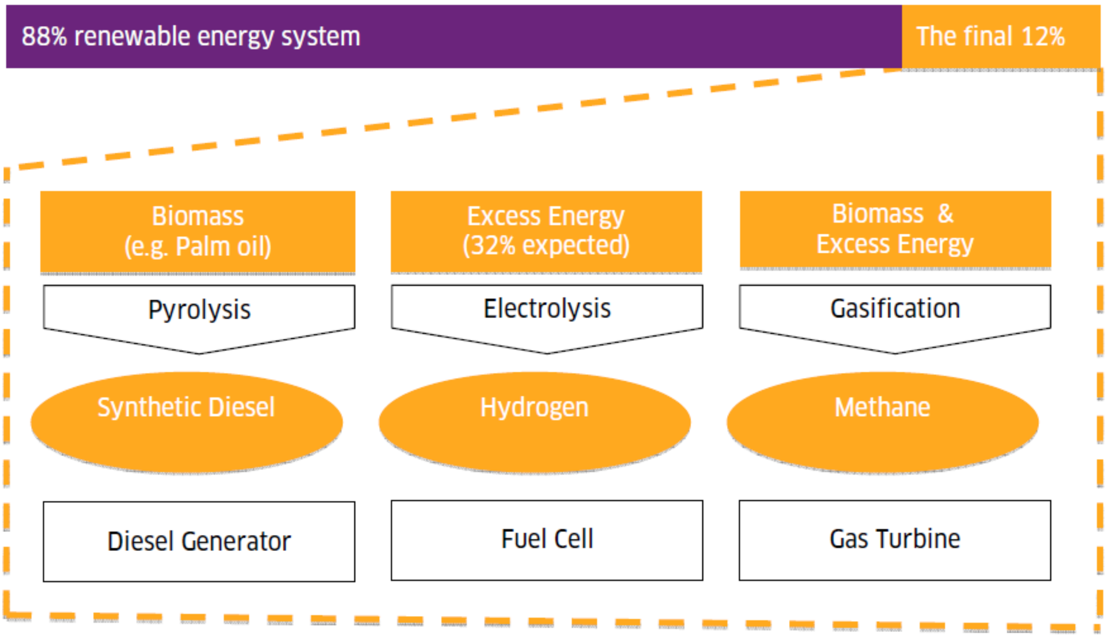


Image 27: Season storage technologies[43]

The hydrogen field is still very young. As a consequence, very few companies, products and subsequently references of commercial project can be found. An analysis shall still be made as prices are available and it appears to be a very promising technology for the future. Companies such as *Atawey* or *Etogas* bet on it as they see it as the only solution to achieve a 100 % renewable system. Both companies still rely on research and demonstration projects.

3 Islands with a high penetration of renewable energy in the electricity grid

In the following the technical and economical characteristics of the islands with an installed or planned installation of a high percentage of renewable energies will be described.

3.1 Islands with already installed high penetration of renewable energies

3.1.1 Tokelau

Like almost all small island nations it used to rely on diesel-powered generators to meet the needs of its 1,400 residents. In its first full year of operation in 2012, the new 1 MW solar system met roughly 93% of the nation's electricity demand of 2.3 MWh per day. Today, Tokelau has reduced its annual fuel bill by about $800,000, which more than covers payments on the loan (7.35 million US dollars) it received from the government of New Zealand for the microgrid.

A large number of inverters were chosen to provide the high power needed instead of a few larger inverters as reliability was the priority due to the remoteness of the location. Unlike smaller inverters, a big inverter needs a fan which is a moving part and thus increasing the odds of failure. [52]

The system is composed of a PV system combined with lead acid batteries and coconut oil in diesel generators for backup. The batteries have been designed to have 1.5 to 2 days of autonomy. Afterwards, the backup generator would be turned on. [53]

Image 28: Tokelau position in the world

3.1.2 Graciosa

5.4MW of wind turbines, and 1MW of solar PV are used to cover a load of 3 MW/12.85 GWh p.a. of 4500 inhabitants. These generation source are combined with two types of batteries with the specifications corresponding to 2.7MW/10MWh. 1.4 MWh of lithium ion batteries are used for their good power characteristics and 8.6 MWh NaS batteries for their good energy characteristics. The total investment was 31.6 Million $.

This means that 100 per cent of the output from solar and wind can be used, the island can consume up to 70 per cent renewable energy by 2018, and save 22.8 Million $ of diesel that needs to be shipped in by tanker on a weekly basis. The next step is to use “excess energy” to turn local bio waste into synthetic diesel from a backup system. That will mean that the island becomes 100% renewable.

Aside from a cable linking the new wind park to the grid, new cables will not need to be installed.[54]

Image 29: Graciosa position in the world

3.1.3 Samsø

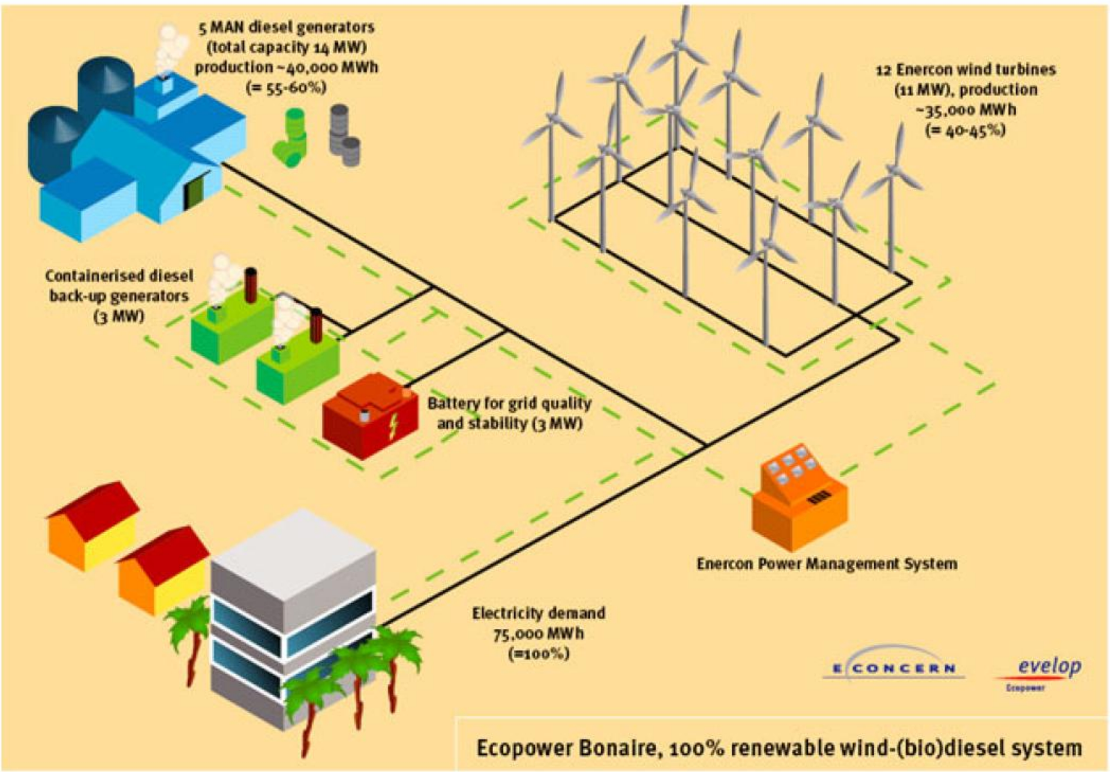
The Danish island of Samsø has 4100 inhabitants and a consumption of 29 GWh per year.

Eleven onshore wind turbines provide 11 MW / 27.9 GWh per year. 10 offshore wind turbines produce 23 megawatts and 77.5 GWh per year. The total energy produced is more than 100 % of the consumed energy. The storage capacity is not enough to consume only the produced energy so most of it is exported and during no-wind days the energy is imported through undersea cables connecting the mainland with the island. [55][56]

Image 30: Samsø position in the world

3.1.4 Bonaire island

With a population of 14,500. Bonaire's peak electricity demand is approximately 11 MW. It consumed 75,000 MWh of diesel-generated electricity.



Courtesy of Ecofys Netherlands BV

Image 31: Bonaire's system components

The system's design includes a hybrid wind-diesel power plant, which will be comprised of an 11 MW wind farm supplemented by a 14 MW biodiesel power plant (in form of algae), and a 3 MW energy storage system in form of *SAFT*'s SMRX block battery design nickel-cadmium battery capable of bridging a two-minute outage of wind. However, the island wants eventually to produce 100% of its electricity from renewables, and within five years' time is hoping to replace the diesel with bio oil from salt water algae grown on the island.

In 2010 the power plant came online but the diesel gensets were still using diesel. The second phase marked by the use of biodiesel in form of algae in the large salt pans on the southern part of the island is being evaluated.

The generators are already equipped to burn both minerals and biofuels.

Once this biofuel is put into use, the wind turbines will be providing approximately 40 percent of the island's total energy needs while the biofuel/diesel generators will provide the remaining 60 percent.

The cost of Bonaire's new wind-diesel system is approximately US$60 million, with an expected return of around $15 million per year.[57]

3.1.5 El Hierro

El Hierro is a canary island with 10000 inhabitants.

Image 32: Upper water storage in El Hierro

Currently there is 12.7MW diesel genset power plant in operation. The construction phase has started to install an 11.32 MW hydropower plant and 11.5 MW of wind power. it is the first to secure a consistent supply of electricity from wind and water only, without the need for supplementary fuel or connection to an electrical grid. Excess power from the five wind turbines will be used to pump water to a reservoir in the crater of a non-active volcano. When winds are calm, this water will be released, flowing downhill through hydroelectric turbines. This way, excess wind power can be saved without the need for batteries. The reservoir has a 500,000 cubic meter capacity and a 530 meters altitude. This roughly equals to 1 GWh of storage.

Though the systems have already been heavily tested, the island does have an emergency reserve of fuel to protect against unforeseen problems.

From October 2010 to September 2011 the load was 44 GWh and the peak demand 7.6 MW. It is expected to grow to 69 GWh in 2031.

The total project budget is €64M (US$86.4M) of which the Institute for the Diversification of Energy of Spain (IDAE) has provided US$47.25M through public funds and the rest coming from private investors.

El Hierro wants to extend its environmental credentials even further by ensuring that by 2020 all of its 6,000 vehicles are run on electricity thanks to an agreement with the Renault-Nissan alliance.

[58][59][60]

3.1.6 Pellworm

Pellworm has 1200 inhabitants, on a 37 square kilometers surface. The electricity consumption is 7 GWh.

70% of the demand is covered by wind. The generation is composed of 5.75MW wind turbines, 2.75 MW PV power, 0.5 MW CHP biogas (corn, manure).
The total generation of 22 GWh more than triples the consumption.
The storage is decentralized with night storage heaters and heat pumps in the range of "hours".
In the end of 2013 battery storage was commissioned. A centralized VRB of 200kW /1.6MWh is used for the "hours to days" storage. The *SAFT Intensium Max* 20 lithium ion battery with a discharge capability of 1MW/560kWh and charge capability of 560 kW is used for the "min to hours" storage and is expected to have a lifetime of 15 years.

The island manages local surpluses and incapacities with a 2 subsea cables connection of 20 kV to the mainland.[61][62] [63]

Image 33: Pellworm's position in Germany

3.2 Islands with planned installation of high penetration of renewable energies

3.2.1 Faial

The island has 15,000 inhabitants and a consumption of 43 GWh per year.
It is powered by six oil-fired generators that produce up to 17 MW of electric power. There are 6 wind parks with 7.1 MW of power and 14.6 GWh energy production p.a. in 2005. *ABB* installed its microgrid plus controller in 2012 allowing to generate 75 % of its energy from renewable energy sources in 2018. [64]

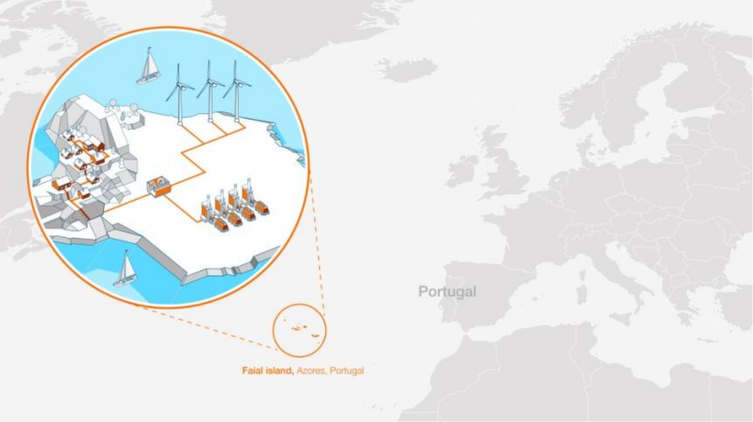


Image 34: Faial's position in the world

3.2.2 La Reunion

Image 35: Reunion position in the world

Based on the *Schéma Régional Climat Air Énergie* or SRCAE, the goal of Reunion (a French overseas departments) is a 50% renewable mix for by 2020 and self sufficiency by 2030.

The population is around 800,000 and the load of the island is 970 GWh.

In 2012 there were 6 hydro power stations (133 MW/ 488 GWh), two wind parks (16.5 MW/ 18.2 GWh), photovoltaics (152 MW / 190.4 GWh), and a biogas facility fueled by organic waste (72 GWh). Nearly 95 solar hot water heaters additionally helped avoid 142.3 GWh of power usage. There are also two bagasse power stations (262.6 GWh), which burn waste from sugarcane.

Making up the fossil fuel portion of the mix were coal (291 MW) and heavy fuel/diesel power plants (220 MW).

A 1 unit of 1MW/7MWh NaS and 9 units of 1 MW / 1MWh lithium ion of *SAFT* are or are planned to be installed as ESS.[65][66][67]

3.2.3 Tonga

Image 36: Tonga's position in the world

Tonga has 106,000 inhabitants and is composed of 176 islands and has a demand of 45 GWh. In 2013 the solar fraction was 4 %.

In 2010 the island was still 100 % relying on diesel and a plan was drafted to switch to 50 % renewables by 2020 [IRENA]

In 2013 a 500 kWp PV plant with fuel save controller was installed in the second biggest island allowing to cover 13 % of the energy consumption.
The project includes storage in form of gel lead acid batteries with 240 kWh of capacity. The PV-diesel system has annual electricity output of 873 MWh. The funding was done by *Masdar*.
Several other projects are planned such as $7 million of PV power projects with funding provided by the Asian development bank and Australia.
[68][69]

3.2.4 Other examples

Neckar island Richard Brandson has started the initiative the 10 island challenge. This is to show that a transition towards sustainable energies is cost effective and achievable. It starts with Neckar island in 2014 where the plan is to reduce fuel consumption by 75 % with a mixture of solar panels, wind turbines and lithium ion batteries. [70]

The Cook Islands, They intend to have 50% renewable energies until 2015. [71]

Gotland (Sweden) has the target of 100 % renewable energies by 2025. It is marked by many onshore, 117 Wind turbines installed by 1999 producing 62 GWh/year, offshore wind turbines and a biomass focus. [72]

Hawaii, Clean energy plan 25% renewable energy in 2020 from 10% 2010.[73]

Cape Verde wants to achieve 50 % of renewables until 2020.[74]

Tuvalu the country now aims to be powered 100 % by renewable energy sources by 2020, a goal requiring an investment estimated at just over $20 million, according to government estimates.[75]

Many more could be mentioned but it was decided to stop here due to time limits.

4 Status quo of the island

4.1 Background and general data of the island

The island has a 200 km distance from the mainland, an extension of **16 km** and an area of 7,515 hectares. The population is growing rapidly. In 2005 there were 5,610 inhabitants, in 2010 already 14,000 and projection for 2015 are of 15,070.

The island is very touristic, not only for international tourism but also for the country's people. It offers not only countryside and nature experiences, but also cultural diversity thanks to its strategic position and history. The future is also very promising due to the touristic expansion which is expected and which will lead to a growth of the electricity consumption in the coming years.

Technical challenges and constraints exist as the location is so far from the mainland (transportation, surface, climate etc.)

[76]

4.2 Generation

The current capacity of the island is mainly with diesel generators sets. The island has two power stations. The total installed capacity is 4162 kW, of which 2500kW is the active power.

One power plant is located in the downtown village, very close to the residential villas, schools and markets. The power plant has 5 diesel generators with a total capacity of 1762kW. The other power plant is located outskirts of the village, on the route to the main port of the island. This one has a total capacity of 2400kW which comes from 4 different diesel generators.

[77]

The grid electricity price based on diesel genset production is 0,39 $ / kWh and the liter diesel price is 1,06 $.

A 2,5 km distant offshore wind power plant is under construction with a capacity of 4 MW. It will be connected with a 22 kV cable connection to the shore and will have an estimated total project cost of 16,37 Million $. These plants are said to provide an electricity at a price of 0,25 $/kWh. [76]

The energy generated by the plants with its self consumption, the losses, the maximal power and the average growth rate from 2009 to 2013 can be seen in the table below.

Years	**2009**	**2010**	**2011**	**2012**	**2013**
Generated energy (kWh)	7.588.767	8.368.629	8.973.693	9.183.468	9.547.329
Self consumption (kWh)	75.332	64.676	63.694	73.075	54.815
Losses technical + non-technical (%)	13,01%	12,92%	13,2%	11,32%	10,47%
Pmax (kW)	1.110	1.250	1.312	1.425	1.550
Average growth rate (%)	12,5	10,4	6,88	4,16	5,35

Table 1: Case study's generation data

The generated energy is constantly increasing and it reached 9.547 MWh in 2013. It is worth to mention that the self consumption (54,815 kWh in 2013 corresponding to 0.5 % of the total generated energy) and the losses (10 % in 2013 down from 13 % in 2009) are decreasing but still very high.
[77]

4.3 Demand

The consumption is mainly residential and commercial (hotels, markets, etc…). The island has also industry and productive users but those are mainly disconnected from the power grid and they run their own diesel generators.

Type	**2009**	**2010**	**2011**	**2012**	**2013**
Total (kWh)	6.601.409	7.287.814	7.789.444	8.113.581	8.547.500
Industry (Fishery, forestry, construction)	Off-grid	Off-grid	Off-grid	Off-grid	Off-grid
Hotel Commerce	2.374.183	2.890.831	3.231.671	2.727.635	2.712.809
Households	2.950.869	3.182.720	3.394.319	4.243.892	3.897.855
Others	1.276.357	1.214.263	1.163.454	1.115.673	1.936.836

Table 2: Case study's demand types

The demand has been expected to be rising. That is probably why an unusually big wind power has been installed.
In the following graph a daily profile of the generated power in the two power plants for the 26th of February can be seen. The graph shows that there is a basic consumption of 800 kW with a maximum reached at 5 pm with 1,500 kW.

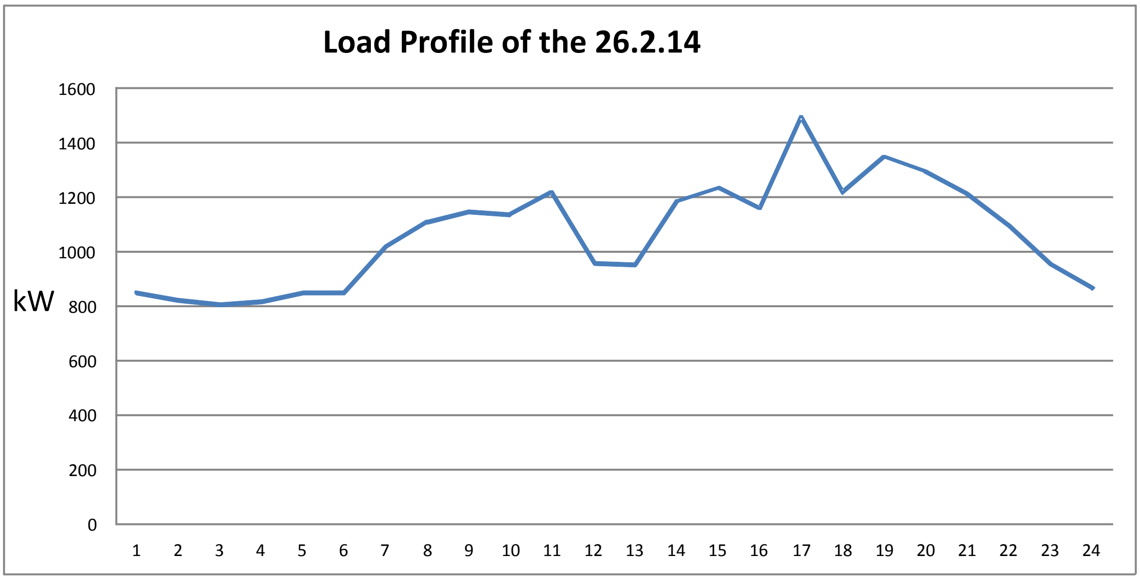


Table 3: Graph load profile of the 26.2.14 in the case study's location

The load was only given for all the hours of a day in February. This was extrapolated into the future for all the days of the year. [77]

4.4 Power distribution

The medium voltage Mini-Grid at 22 kV has been upgraded from 15 kV. There is also an overhead low voltage line of more than 12km length.

Most of the cables have a 120 mm cross section and as consequence the current grid cannot handle more than 1250 kVA in one part of the island and 800 kVA for the other part.[77]

5 Simulation of scenarios with different penetration levels of renewable energies for the island

5.1 Methodology

The software ***Hybrid optimization model for electric renewables (called HOMER)*** is used for a techno-economic optimization of the whole system.
HOMER runs a chronological simulation with an hour-by-hour energy balance that considers economic inputs to determine how the energy system's components are dispatched. It results in an optimized NPC. page 50 [78]

To run the simulations a variety of technical and economical inputs have to be introduced.

Technological inputs

For the Size (kW) several values are introduced in order to find the optimum. The software calculates and automatically suggest iterations for certain components.
One value was chosen for each component's Capital cost ($), Replacement cost ($), O&M ($/yr), Lifetime (years), Efficiency (%).

Economical inputs

All the following values were set annual real interest rate (%), Project lifetime (25 years), system fixed capital cost ($), system fixed O&M cost ($/year), capacity shortage penalty ($/kWh).

The outputs were economical and technological as well:
A cost summary, salvage, cash flow, electrical output data for each technology.
The salvage value corresponds to the remaining value in monetary terms of the components at the end of the project's lifetime.[79]

In the following an economical optimization of the NPC for different configurations is going to be made over an analysed period of 25 years. Diverse scenarios with the goal of increasing the renewable energy share will be looked at. The variables are: more generation power, grid stability devices such as flywheels and storage devices.

The NPC optimization is not necessarily the objective of all system operators. Often a low CAPEX and quick return on investment are more important. As HOMER optimizes the NPC and this is often taken as a reference, this will be the objective in this work. In the same time it will be tried to maximize the renewable energies'. Excess electricity might be possible but is not a problem as long as the costs stay low. This extra energy could eventually be used in the future for an increasing demand or for new applications such as heating or electric mobility. [80]

5.2 Assumptions

5.2.1 General economic assumptions

The assumptions taken are that

- 100% own money or equity is used which leads to no interest rates.
- The annual real interest rate is assumed to be 2 % as it corresponds to the yearly average of the last 5 years of the location. [81]
- Costs of unmet electrical load is low in this location as cost of supplying constant power is very high and a small unmet load is acceptable from a social perspective in this location. No capacity shortage penalty is claimed. Capacity shortcuts are set to not exceed 2 %.
- Project lifetime is set to be 25 years.
- An euro equivalence in dollars of 1.28.

5.2.2 Techno-economic assumptions

A large scale generation with a high renewable energy penetration will be deployed. The communication between these large powers has to be guaranteed. A central configuration facilitates the communication between the components (generators, converters and storage units to a distributed one as). Being more reliable, it is therefore preferred to a distributed configuration.

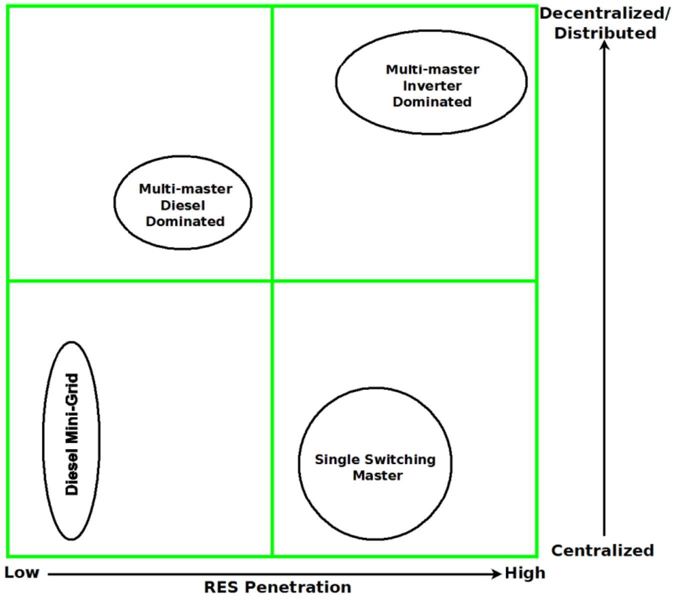


Image 37: centralized-distributed configuration vs. RES penetration[19]

Another important point is the cable's capability. It cannot transport more than a certain amount of amperes. Therefore, the high power of the wind turbines has to be transported through specifically designed cables directly towards the batteries that would be connected to the current grid that cannot handle more than 1250 kVA in one part of the island and 800 kVA for the other part. The batteries could then deliver current in the allowed range.

5.2.2.1 Energy Generation

Based on constraints of the island and prices some technologies are discarded from the start:

Geothermal and hydropower: No resource is present; The location is very far from any tectonic plate and no river is in the island.
Biomass: Some type of crops have a resource that is either difficult to estimate (rice husk, coconut oil) or there is no resource at all.

As confirmed in the disruptive technologies, the analysed and most relevant ones are the wind and the solar energy in combination with the diesel genset.[8]

- Wind

The wind speed was given by NASA and by measurements of the local weather station. A double optimization for both wind speed profiles of a multitude of scenarios would have been too data intensive. As the NASA wind speeds seemed too high (the capacitor factor of the wind turbines was exceeding 50 %) and the local weather station yielded very low wind speeds (the capacitor factor of the wind turbines was at 13.5 %) an average of both wind speed profile was made and then rounded up.

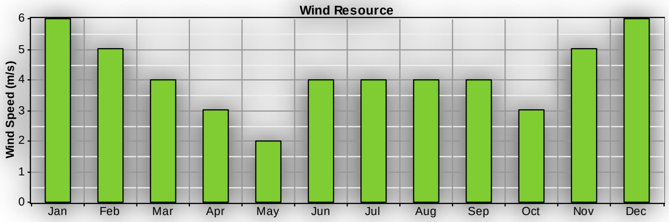


Image 38: Wind resource in m/s per month of the island

Both wind speed profiles were given for a different altitude than the nacelle of the wind turbine. The Prandtl equation of the boundary layer was used to account for the altitude difference even though it mainly changes if obstacles are present which is not the case on the open sea.

The autocorrelation factor (0.85) and the Weibull shape parameter (k=2) were left unchanged due to unavailable data.

One important assumption regarding the renewable resource in form of wind speed is that it is considered to stay constant during each hour. In other terms, there is no minute variation. In reality the wind speed varies significantly in a minute range. [23]

The offshore project on the island was about 4500 $ / kW which is much higher than equivalent projects mentioned by the DOE of the USA. On the one hand, the much higher cost is justified by the remoteness of the location and the extra costs for building the turbine offshore. On the other hand, it can be assumed that the cost of transport, installation and cables are included in the cost of the whole project. [76][83]

From the already modeled wind turbines in HOMER the one with the highest power has 1,650 MW which is lower than the 2 MW that are planned to be installed. A 2 MW turbine has been created inside HOMER using the data of the turbine manufacturer *Vestas* of its model V110.
Subsequently, 2 of these turbines have been modeled with 4500 $ / kW capital costs and a total cost of $6.9 million per turbine. The replacement costs are estimated to be slightly lower with $5 million as wind turbines are projected to decrease their costs in the future. O&M have been calculated to be a bit higher than the assumed 23 $ /kW/ year that the DOE based mainly on projects in the USA. This is due to the fact that there is much less experience with O&M of the wind turbines in the case study's location than in the USA. 30 $ / kW / year were assumed here.
The transport costs are included in the total cost above and the lifetime was approximated to 15 years.

- Solar PV

The daily and annual solar data was directly retrieved from the locations geographical coordinates (in terms of kWh/kWp p.a.).

An 8º slope is chosen to be optimally inclined towards the sun.

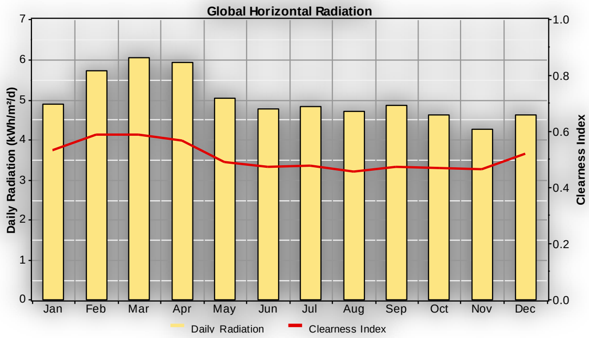


Image 39: Global horizontal radiation in kWh/m2/day for each month

The solar irradiation stays in a similar range throughout the year with a peak in March and a base in November which is normal for locations close to the equator. This stability in resource availability is useful considering the storage aspect.

A close collaboration with the company ATERSA and herewith reliability in data lead to the choice of using the module 240 Wp. For these modules there is a guarantee that they still possess 80% of the original power after 25 years and they continue producing power after this period. [84]
From the given ATERSA module cost a price of 0.80 $ / Wp is found out. [84]

Cables and other balance of system (BOS) components are considered to take 5% of the total costs as in the Tokelau project. A 10% price reduction is assumed as a slight

cost decrease is assumed in time (2013 Tokelau vs. 2015 or later in the case study).
A cost of 0.29 $ / Wp is calculated.

The inverter costs are shown below in the converter part but are included in the PV costs in HOMER.

The freight of a 40" container to the mainland close to the destination costs 1681 $; Considering 560 modules per container and 240 Watt per module yields 0.0125 $ / Watt. The transport cost from the mainland to the island is assumed to be equal.
This gives a total transport cost of: 0.025 $ / Watt.

Total module cost: 1.115 $ / Watt + 0.2 $ / Watt installation (25 % of the cost of all installed components [80]).
For HOMER the inverter is added to the PV costs with the calculation above resulting in an accumulative cost of module, inverter and installation cost of approximately 2 $ / Watt.

- Diesel genset

The gensets' CAPEX is assumed to be equal to 0 as the generators have already been bought. Likewise, the transport is considered to be nil. As the CAPEX of the gensets is rather low in comparison with the other components the effect on the LCOE is rather negligible. The replacement cost is 250 $ per kW as it is a genset above 100 kW. [80]

In HOMER the operating and maintenance cost are assumed to be $0.015/kW per hour. The genset fuel efficiency is left at the most common 3.5 kWh/l.

The lifetime depends on the usage. The factors influencing the lifetime are partial load condition, often start/stop frequency, cold or war starting and the regularity of the maintenance. For diesel gensets from 500 kW to 1 MW which is assumed to be similar to bigger diesel gensets, depending on the usage it goes from 40.000 to 100.000 hours maximum. [85]
As the exact conditions that will be present are unknown and hard to estimate, an average lifetime of 70.000 hours is chosen.

5.2.2.2 Energy conversion and flow management

Converter

For the inverters, it can be considered that above 100 kW the price per kW stays constant and that redundancy is often paramount in order to avoid a system's failure.
In most of the cases the transport and installation of small inverters is cheaper than a centralized one. This is analogue to other components (e.g. batteries).[82]

The converter will be of high power in order to allow all the energy from the generation to be converted in order to be stored in the batteries. For the high power of over 1 MW requested in the island only a big inverter can be considered. The Sunny island inverters for example are limited to 300 kW.

The estimate costs of such a big inverter are based on the Tokelau project. There were battery inverters and string inverters. The installation was in 2013 and with 960 kWp PV power it was smaller than the one to be installed in the case study. Due to the different purchasing times and subsequent price decrease, the price in Tokelau of 831 $ / kW has been estimated to be 20 % more expensive than the one in case study. Therefore, 665 $ / kW is assumed for battery and string inverter and DC charge controller. The price decrease is stronger than the one of the BOS because the learning curve has been steeper in the last years. The replacement will be cheaper with 600 $ /kW.

Battery inverter cost are included in the component called "converter" in HOMER.
PV string inverter price is to be added in "PV price" in HOMER.
After a lifetime of 12.5 years the converter has to be replaced.[53]

DC charge controllers could be included in the design options. Less string inverters would be installed as they would be replaced by charge controllers. The extra energy that would not be used for covering the demand directly would charge the batteries.
If more PV power is installed than the peak demand power then the difference will be the power of the charge controller. In order to simplify the design and to use as many similar parts as possible for an easy maintenance DC charge controller were not chosen. Instead the PV power would be covered by string inverters completely.

Flow management

In all the scenarios, there is no extra operating reserve as percentage of the load.
Some controller can be strictly used for PV modules and not wind turbines. The *SMA* fuel save controller can strictly be used with PV. Its cost lies approximately at 30.000 $.[52]
ABB's *Microgrid Plus System* can be used for any technology which makes it an appropriate choice. The price for the latter one varies depending on the application as for each case a new development has to be made. A 60.000 $ price is assumed as it is more flexible than the *SMA* product but needs to be developed for each application. It is a onetime cost independent of the components' power.[86]

This cost will be included in each wind turbine cost (30.000 $ per unit) as it is a fixed cost, the wind turbines having a fixed power unlike the other components that vary their power and hence a cost per power.

If there is an excess energy of the wind turbines i.e. more generated power than the load demands, an automatic pitching sets in curtailing the wind power.

5.2.2.3 Short term grid stabilization

The model chosen is the *Beacon Power Smart Energy 25* that was already present in the HOMER library.

As there was only price information available for the *Powerstore*, a cost of approximately 600.000 $ for the unit of 500 kW, the same kW price, 1200 $ / kW, was assumed for the Beacon flywheel of 100 kW. The replacement cost is assumed to be a bit lower with 1000 $ /kW thanks to future cost reduction with increased production [86].

The efficiency is 85%. An O&M cost of 1.5 % of the CAPEX is assumed corresponding to 2000 $ for each Beacon flywheel unit.

The lifetime changes depending on the usage, an exact approximation is difficult to make as the provided wind speed data is not detailed enough. Therefore, a 20 years lifetime foreseen in the technical specifications is assumed.

Batteries will be looked into in the energy storage section.

5.2.2.4 Energy Storage

Lithium ion batteries, high temperature batteries

Lithium ion and high temperature batteries are not analysed due to missing information in HOMER and the difficulty to obtain the necessary curves such as capacity to discharge current curve.

Lead acid batteries

From the catalog of *Albasolar* a public price of 1563 € or 2000 $ for the unit of 24 OPzS 3000 of FIAMM with 8 kWh is given. Due to the large amount of bought batteries the cost is estimated to be reduced by 35% to 1000 € or 1200 $.

From the Energy Storage Technology Review a price of O&M of 20$/kWh/year was found.

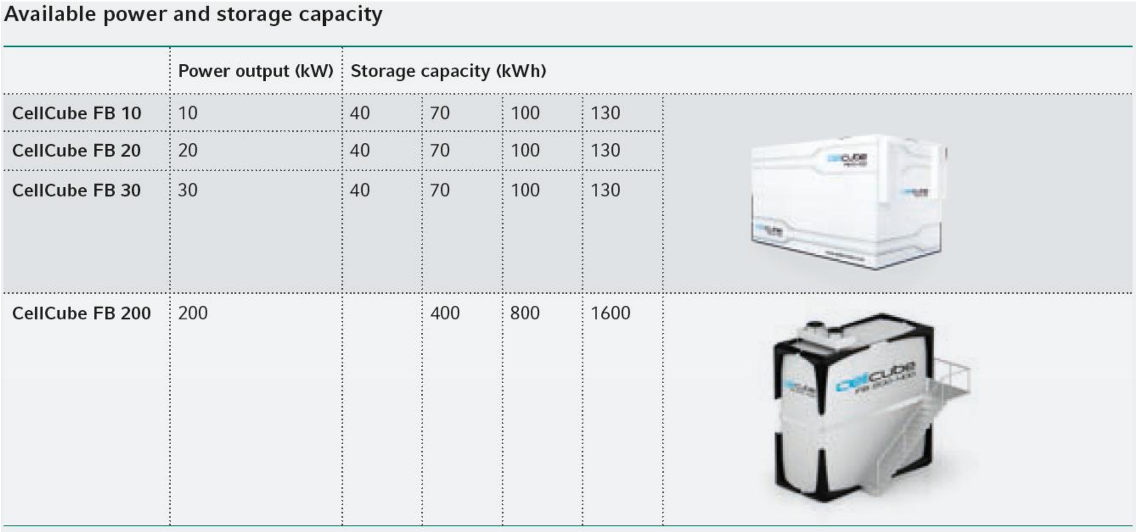
Image 40: Hoppecke 24 OPzS 3000

The lead acid batteries present in HOMER are the *Hoppecke* 24 OPzS 3000. The specifications are 2 V, 3000 Ah at C100 which is equivalent to 6 kWh, efficiency of 86% and considering a similar price as the batteries above, the unit cost would be of 3/4 of 1200 $ equal to 900 $.

The lifetime depends on the DOD. The minimal state of charge (SOC) is 30 %.

Vanadium redox flow batteries

The Vanadium redox flow batteries present an 80 % efficiency and an up to 20 years lifetime. In the simulation a 15 years lifetime is assumed as it was set in HOMER.



Available power and storage capacity

	Power output (kW)	Storage capacity (kWh)			
CellCube FB 10	10	40	70	100	130
CellCube FB 20	20	40	70	100	130
CellCube FB 30	30	40	70	100	130
CellCube FB 200	200		400	800	1600

Image 41: Available power and storage capacity of the Cellcube [18]

Gildemeister's *Cellcube* offers a modular solution with A FB 10-40 cost about 100,000 € a FB 30 130 about 200,000 € or 253,000 $ that can be extended to the MW range. A price of 500 $ per kW of cell stack and 1500 $ per kWh of electrolyte corresponding more or less to the proportion of the FB 30 130 is assumed. The manufacturer stated that a similar cost proportion is present for higher capacity batteries.
For the O&M 0.005 $ / kWh throughput is left unchanged as assumed in HOMER.
The minimal SOC is 0%.[18]

Hydrogen system

The PEM electrolyser has a cost of 4100 US $ / kW, a 73 % efficiency and a lifetime depending on the usage of about 30000 hours. [87]
For the h2 tank, 1 kg of storage at 30 bars costs 535 $ and the O&M is assumed to be 5 $ / year with a lifetime of 25 years.
The PEM fuel cell has a cost of 5100 US $ / kW, a 50 % efficiency and a lifetime depending on the usage of about 30000 hours. [88][89]

5.3 Simulation, results and discussion

The technologies used for each location to cover the demand depend highly on the load profile. If it follows the renewable resource the system will be very different to a load that does not match it at all. In practical terms, if the load is present when the sun shines the amount of storage that is necessary is very different i.e. much lower than in the case of a night load.

The pathway is subdivided in 4 steps varying depending on the penetration level of renewable energies; the low penetration, the medium penetration, the high penetration and the 100 % renewable energy system scenarios.
In the low penetration scenarios different theoretical configurations (PV scenario and only gensets scenario) will be analysed just for the sake of comparison. In reality the decision to implement the wind turbine scenario with two 2 MW wind turbines has

already been taken by the location's government.

5.3.1 Low penetration

Different generation configurations are compared.

5.3.1.1 Only gensets

In the only gensets mode, all the load is covered at any moment by the gensets.
A 1.4 MW diesel genset (here marked as label) is installed. As the acceptable limit of 2 % capacity shortage was allowed, the peak power of the diesel genset does not match the peak power of the load.

Label Production	**Tot. Electrical Production**	**AC Primary Load Served**	**Ren. Fraction**
kWh/yr	kWh/yr	kWh/yr	
9,293,995	9,293,995	9,293,995	0.00

Table 4: Energy production of installed components

The energy produced by the genset never exceeds the one demanded by the load.

Cap. Shortage	**Unmet Load**	**Excess Electricity**
kWh/yr	kWh/yr	kWh/yr
33,215	33,215	0

Table 5: Excess and unmet energy

The unmet load corresponds to the energy lost due to the 90 kW difference between the generator power and the load's peak demand.

Component	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generator 1	771,545	3,591,535	68,388,656	-185,907	72,565,816
System	771,545	3,591,535	68,388,656	-185,907	72,565,816

Table 6: Cash flow summary

The salvage is rather low in this case meaning that the components should be exchanged soon after the end of the project lifetime.
The capital cost is not included as it is 0, the diesel gensets being already present in the island.
This system yields a high LCOE of 0.4 $/ kWh essentially completely deriving from the high fuel cost.
The only genset mode yields an expensive system without any renewable energies. The very high $72 million NPC due to the high OPEX is counterposed by a non-existing CAPEX.

5.3.1.2 PV

The PV scenario is similar to the wind turbines one, with the difference of using the sun instead of having the wind as the renewable energy source. A smart control system (like the Fuel save controller (FSC) of *SMA*) has to be provided along with the diesel gensets that are used for the grid forming and the spinning reserve. This control system allows for a safe and optimal operation. An assumption is that at any moment the diesel gensets are working at 30 % of their nominal power as they would be damaged otherwise.
Also they always have to stay on as a full spinning reserve corresponding to the load.

- PV
- controller
- gensets

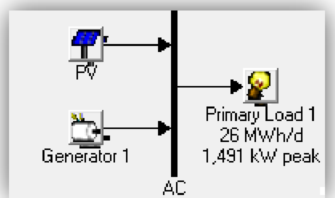


Image 42: PV system diagram

The diesel gensets are still running all the time but they adapt their power to the intermittent PV power.

PV	Label
MW	MW
1.5	1.5

Table 7: Power of installed components

The optimized pv and diesel genset power are the same with 1.5 MW corresponding also to the peak demand. As the PV modules are not available at certain times or even not available at all from 6 pm to 6 am, the diesel genset power has to be at least in an admissible range from the peak power of the demand to not exceed the 2 % capacity shortage. That is why a 1.5 MW power was installed. (1.4 MW would have probably also been possible)

PV Production	Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction
kWh/yr	kWh/yr	kWh/yr	kWh/yr	
2,219,476	7,550,325	9,769,800	9,327,210	0.19

Table 8: Energy production of installed components

The renewable fraction of a 2000 kW PV plant is 22 % which is 3 % higher than the renewable fraction of a 1500 kW plant.

The PV production is concentrated in the months from September to April. Of course the sun's irradiation being stronger during the noon hours the PV power is highest during these times. From 6 pm to 6 am the production is constantly null due to the proximity to the equator and therefore very small seasonal variation in the days lengths.

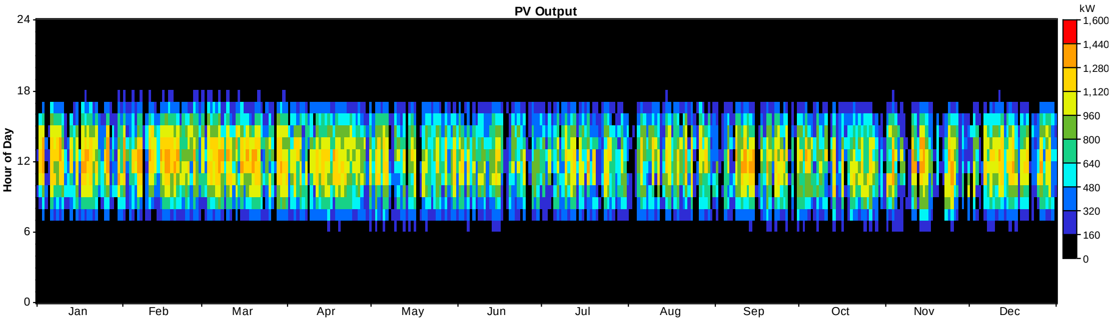


Image 43: PV energy production throughout the year.

Cap. Shortage	Unmet Load	Excess Electricity
kWh/yr	kWh/yr	kWh/yr
0	0	442,571

Table 9: Excess and unmet energy

No storage is installed. The diesel gensets are forced to be running at least for the spinning reserve. Thus, even though the PV power is not higher than the peak demand, some excess production occurs leading to a loss of roughly 450 MWh.

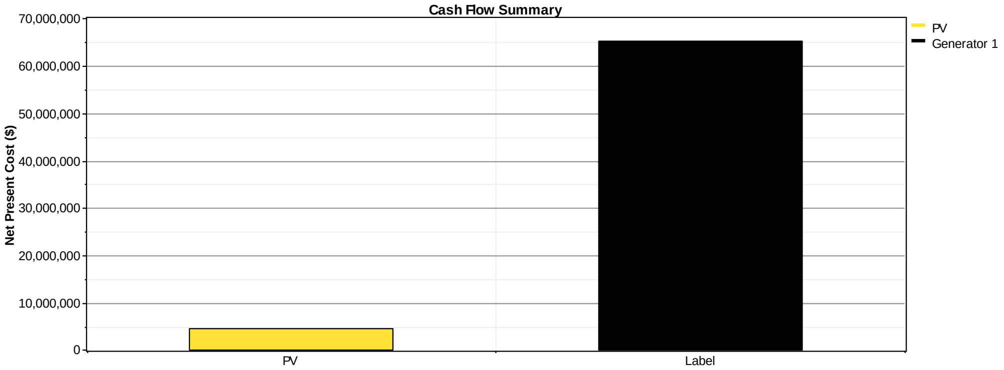


Image 44: Cash flow summary

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	3,000,000	0	1,464,260	0	0	4,464,260
Generator 1	0	826,655	3,848,074	60,817,584	-199,186	65,293,128
System	3,000,000	826,655	5,312,334	60,817,584	-199,186	69,757,384

Table 10: Cost structure

This scenario is marked by a dominance of the genset with $65 million vs. $4.5 million for PV. The CAPEX of $3 million being all caused by PV and the remaining OPEX almost all by the gensets.

This system yields a 2 cents lower LCOE of 0.383 $/ kWh in comparison to the only genset scenario.

The NPC is lower with a PV power of 1500 kW than for a higher PV power. As a higher PV power also allows for a higher renewables share the owner has to make the decision about which parameter is more important.

For instance a power of 1500 kW yields a NPC of $69.75 million and a renewables share of 19 % where as a power of 2000 kW yields a NPC of $70 million and a renewables share of 22 %. Of course, the CAPEX are higher for the 2000 kW system as well.

5.3.1.3 *Wind turbines*

If wind turbines such as the V110 2 MW wind turbines of *Vestas* are added, a smart control system (like the *Microgrid Plus System* from *ABB*) has to be provided along with the diesel gensets that are used for the grid forming and the spinning reserve. This control system allows for a safe and optimal operation. An assumption is that at any moment the diesel gensets are working at 30 % of their nominal power as they would be damaged otherwise.

Also they have to stay on as a full spinning reserve corresponding to the load at any moment. The configuration with one and two wind turbines is compared.

- Wind turbines
- controller
- gensets

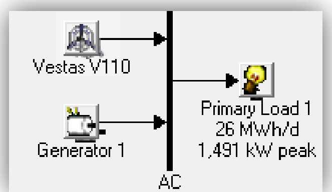


Image 45: Wind system diagram

The diesel gensets are still running all the time but they adapt their power to the intermittent wind turbines' power.

A much higher wind power, 4 MW, than genset power, 1.4 MW, is installed. For covering the load without exceeding the 2 % capacity shortage, 1.4 MW of genset power is enough even in the case that the wind turbine should become unavailable for a longer time e.g. due to maintenance reasons.

V110	Label
2 MW/unit	MW
2	1.4

Table 11: Power of installed components

The very high power in comparison to the demand and the missing storage leads to a high excess power, of almost half of the production (8 GWh seen in table below), that is lost. Nevertheless, it allows to have a rather high renewable energy penetration of 51 %.

Cap. Shortage	Unmet Load	Excess Electricity
kWh/yr	kWh/yr	kWh/yr
33,215	1,226	8,398,280

Table 12: Unmet and excess energy

With the high power of 4 MW of the 2 wind turbines the production profile is highly dominated by them most of the year except for the months of May in particular and in a minder importance October.

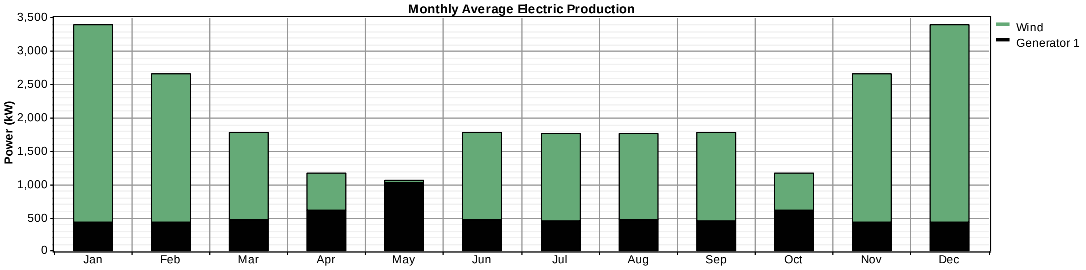


Image 46: Monthly average electric production

Wind Production	Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction
kWh/yr	kWh/yr	kWh/yr	kWh/yr	
13,150,128	4,574,114	17,724,242	9,325,984	0.51

Table 13: Energy production of installed components

With 1 wind turbine the renewable fraction is slightly lower at 45 %.
The diesel genset is almost completely inactive from November to February and during noon hours the reason becoming evident by seeing the wind production being extremely high during these times.
Opposed to that during the month of May and it is almost completely covering the demand.

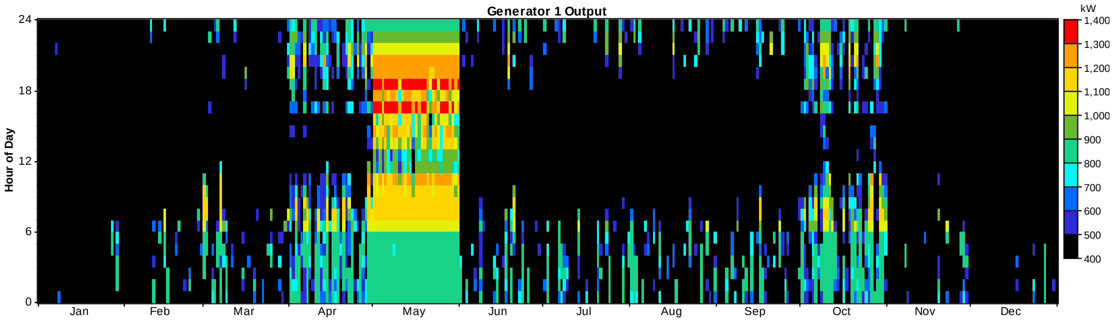


Image 47: The diesel genset production throughout the year

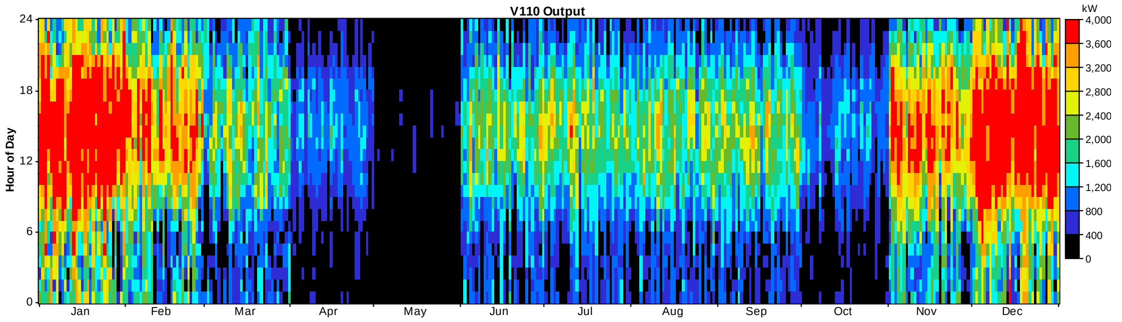


Image 48: Wind energy production throughout the year

From the graph above, the much higher capacity factor of wind in comparison to pv can be appreciated. Nevertheless the pv power is more stable considering that the wind production is almost completely absent in May.

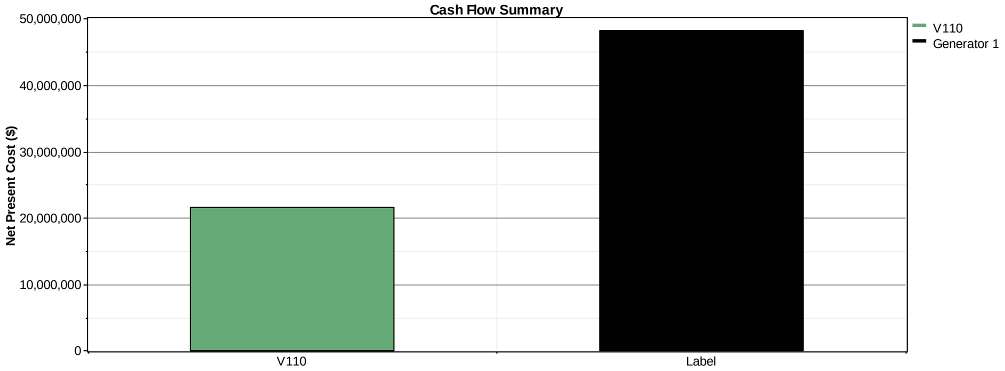


Image 49: Cash flow summary

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
V110	13,860,000	7,430,150	2,342,815	0	-2,031,771	21,601,196
Generator 1	0	771,545	3,591,535	43,969,292	-185,907	48,146,468
System	13,860,000	8,201,694	5,934,351	43,969,292	-2,217,678	69,747,656

Table 14: Cash flow summary

The consequence of having a substantial CAPEX from the wind turbine and an important OPEX from the fuel is a pretty high total cost but slightly lower NPC than the only genset scenario of $69.7 million.

This system yields a LCOE of 0.383 $/ kWh.

For 1 wind turbine the LCOE would be 0.34 $ / kWh and the NPC $62 million.

The compared scenario with only one wind turbine shows that most of the energy created by a second turbine is lost. The renewable energy share is only slightly increased to 51 % from 45 %.

The excess energy loss could be said to be the proof of a bad design of the turbines. Taking into account that the demand might increase and that storage might be installed in the future, installing 2 wind turbines might be a reasonable decision to save the higher cost of 2 separate installations.

5.3.2 Medium penetration

Starting from the medium penetration scenarios, the diesel gensets are only used when the renewable energy source is not producing the required quantity demanded by the load, the spinning reserve of the flywheel is consumed or the batteries' SOC has reached its critical minimum level of 30%.

As the HOMER algorithm still forces the diesel gensets to run during times when the wind production is exceeding the load demand in order to recharge the flywheel's capacity when the flywheel capacity is not full, the minimum load ratio of the genset was set to 0 which automatically shuts them down when there is an excess of wind power. It has to be acknowledged that in reality the minimum load of the best diesel gensets (e.g. of the company *Hatz*) is 10 %. Between a wrong energy control mechanism and a wrong diesel genset control a trade-off had to be chosen.

Depending on the demand profile some system's configurations are more beneficial than others.
If the demand is constant then the string inverter should match the PV power. If the demand is low during the most intensive sun hours then a charge controller allowing to charge the battery with the excess PV power can be added to avoid more conversion losses (DC-AC-DC).
In the project of Tokelau for instance the charge controller, battery inverter and string inverter were varying in power. The load was more shifted towards the night.

In the case study's scenarios the demand being mainly daily no charge controllers are designed to replace the string PV inverter power.

A controller as the *Microgrid Plus System* managing the energy dispatch will also be included in all the following scenarios.

In an extreme case, a diesel genset needs 30 seconds to arrive from 0 to its nominal power depending on the model. If this is done frequently, it damages the engine. That means that the spinning reserve of the flywheels has to be at least 30 seconds in order to allow the diesel gensets to recover the lost wind power. The Beacon flywheel unit has a 90 MWs capacity which is more than enough for this purpose. The problem lies more within the required power as the rated power is 100 kW which indicates that if the demand is 1 MW, 10 units would be needed if no wind power and diesel gensets are available. Hence, 10 units would be installed as a minimum to cover the average demand. 10 units would allow to provide 1 MW of power for 900 seconds which is more than the recommended 5 minutes enough for ramping up the diesel gensets in a smooth way in case of unavailability of the renewable resource.
This duty can also be achieved by batteries, a case that will be used as a comparison.
The operating reserve is provided by the flywheels or batteries.

5.3.2.1 Flywheel

In the flywheel scenario a converter is added but it is assumed to be ideal (100 % efficiency and 0 costs). This is the way it is modeled in HOMER as no converter would be needed in practice given that the flywheel is already an AC device.
[source HOMER flywheel modeling]

- Wind turbines
- Flywheel
- Diesel gensets

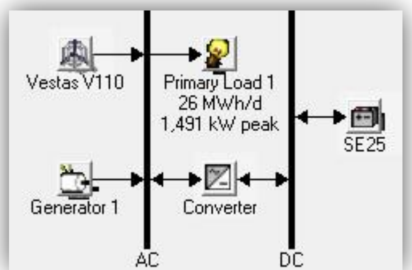


Image 50: Flywheel system diagram

The energy produced by the wind turbines (*Vestas* V110) is always used to cover the loads with a stabilization of the flywheel (SE 25 and Converter). When the wind power is less than the load then the flywheel takes over for a short period of time before the diesel genset (Generator 1) takes over.

V110	Label	Beacon Smart Energy 25	Converter
2 MW/unit	MW	100 kW / unit	MW
2	1.5	10	1.6

Table 15: Power of installed components

Comparing the electricity production of the flywheel and the wind power scenario, especially looking at the situation in May, it becomes clear that the flywheel allows the wind production to increase its share. This avoids energy losses.

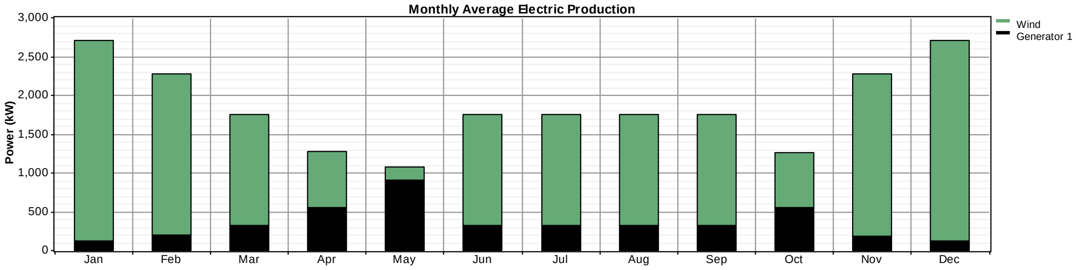


Image 51: Monthly average electric production

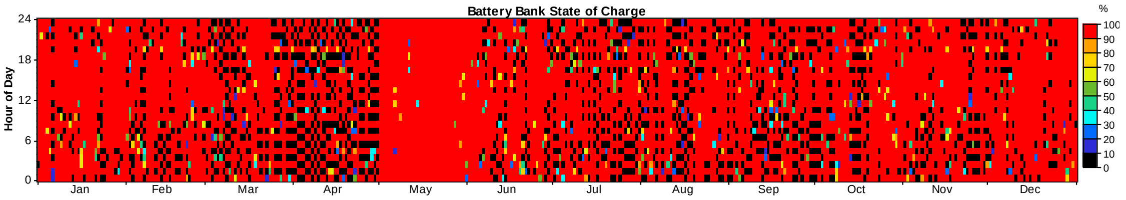


Image 52: Flywheel production throughout the year

The production profile of the flywheel is a constant daily switching from fully charged to fully discharged. Most of year it is charged though. It makes sense as it has a small capacity and it adapts to the large hourly changes very often.

Wind Production	Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction
kWh/yr	kWh/yr	kWh/yr	kWh/yr	
13,156,002	3,135,333	16,291,335	9,327,210	0.66

Table 16: Energy production of the system

The genset production is more than 1 GWh lower than in the wind turbine scenario so even though the production of the wind power plants is not increasing the renewable fraction sees a growth from 51 % in the wind scenario to 66 % in the flywheel scenario.

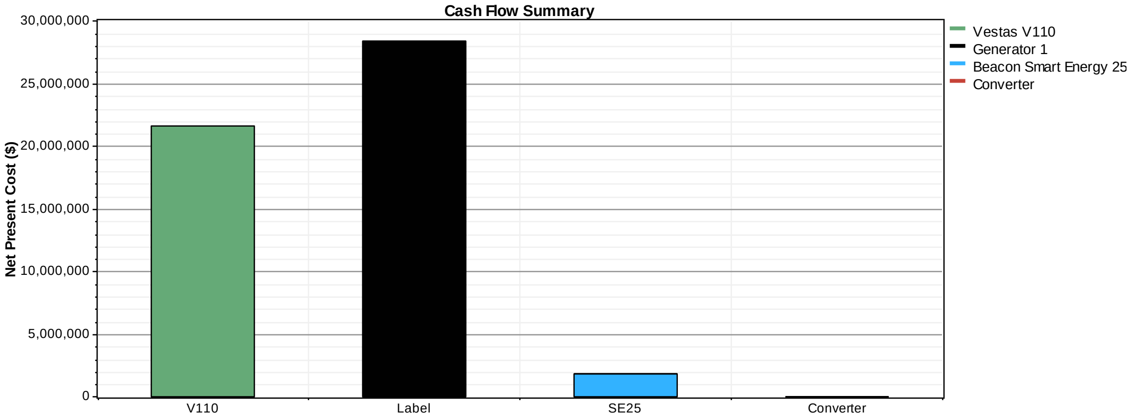


Image 53: Cash flow summary

The cost structure is dominated by the genset and the wind turbines. The flywheel contributes with its almost $2 million to less than 5 % of the total costs.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Vestas V110	13,860,000	7,430,150	2,342,815	0	-2,031,771	21,601,196
Generator 1	0%	267,335	1,799,282	26,393,216	-122,777	28,337,056
Beacon Smart Energy 25	1,200,000	672,972	390,469	0	-457,148	1,806,292
Converter	0	0	0	0	0	0
System	15,060,000	8,370,456	4,532,566	26,393,216	-2,611,696	51,744,544

Table 17: Cost structure

This system yields a $0.1 lower LCOE equal to 0.284 $/ kWh in comparison to the wind turbine scenario it is roughly 33 % lower. In NPC terms it translates to $69 million vs. $51 million.

The fact that the minute variation is neglected can have an effect on the results. This can be seen in the frequency histogram in which the flywheel just has 2 states, either fully charged or fully discharged in opposition to the small lead scenario that shows a stronger variation.

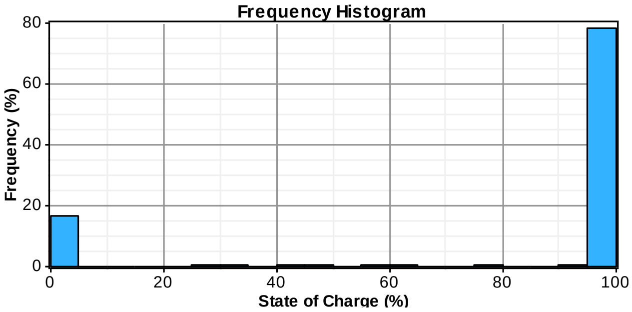


Image 54: Frequency histogram of flywheel

5.3.2.2 small lead

This scenario with a small capacity of lead acid batteries is being done to have a comparison with the flywheel scenario. The impact of adding PV modules is also studied. PV modules might be unnecessary as the energy demand could be covered with the wind power production with coupled storage alone. However, as more storage capacity is not an option in this scenario it might be more economical to install PV modules for the use in the times without wind production instead of the diesel gensets.

- Wind turbines
- PV modules
- small capacity lead acid batteries
- Diesel gensets

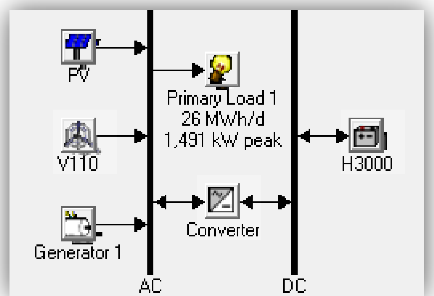


Image 55: Small lead acid battery system diagram

The energy produced by the wind turbines (*Vestas* V110) and the PV modules is always used to cover the loads with a grid stabilization of the small lead acid battery capacity (H3000 and Converter). When the added wind power and solar power is less than the load then the battery takes over for a short period of time before the diesel genset (Generator 1) starts to operate. When added wind power and solar power exceed the demand, the battery's capacity is recharged and once that is accomplished the energy is lost through automatic pitching or inverter Mppt changing.

PV	V110	Label	*Hoppecke* 24 OPzS 3000	Converter
MW	2 MW/unit	kW	Nominal capacity MWh	kW
1	2	800	720	200

Table 18: Power of installed components

The converter power is designed to be smaller than the battery throughput as it is more economical at some occasions to use the diesel generator than to use the battery's capacity. This is a consequence of a high and often occurring discharge current with high DOD lowering the lifetime of the battery which makes the system more expensive.

The lifetime of the battery with a converter of 200 kW is 7.21 years where as a system with exact same parameters but a converter of 500 kW yields 5.87 years of battery life.

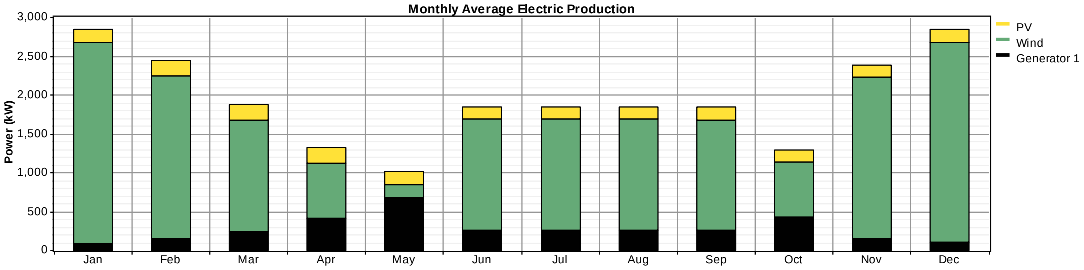


Image 56: Monthly average electric production

As with previous scenarios the energy production is dominated by the wind turbines with May being dominated by the diesel genset due to very low wind speeds.

PV Production	Wind Production	Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction
kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr	
1,478,568	13,150,492	2,437,024	17,066,084	9,151,266	0.72

Table 19: Energy production of installed components

Comparing the total energy production with the consumption reveals yet again that the excess power is substantial.
The renewable energy fraction reaches a pretty high 72 % which is 20 % higher than the scenario without stabilization devices.

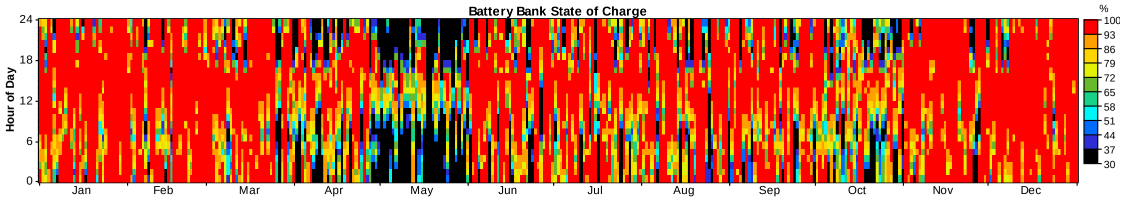


Image 57: lead acid batteries production throughout the year

The battery is very often left unused at 100 % SOC, with May as the big exception.

The frequency histogram is different than the one of the flywheel. Even though both scenarios have a clear dominance of the 100 % SOC, in this scenario all possible SOC until the 30 % battery limit are present. This indicates a higher flexibility but as mentioned before it is probably a flaw of the software.

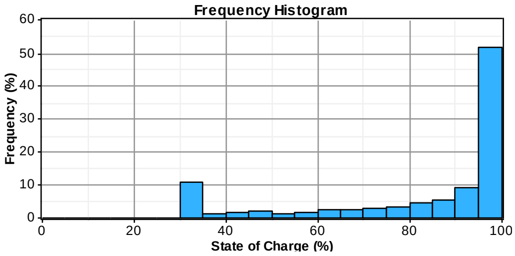


Image 58: Frequency histogram of the small capacity lead acid battery

Cap. Shortage	Unmet Load	Excess Electricity
kWh/yr	kWh/yr	kWh/yr
175,946	175,946	7,841,149

Table 20: Unmet and excess energy

The still pretty small battery capacity leaves the excess electricity of over 7.8 GWh per year at a very high level.

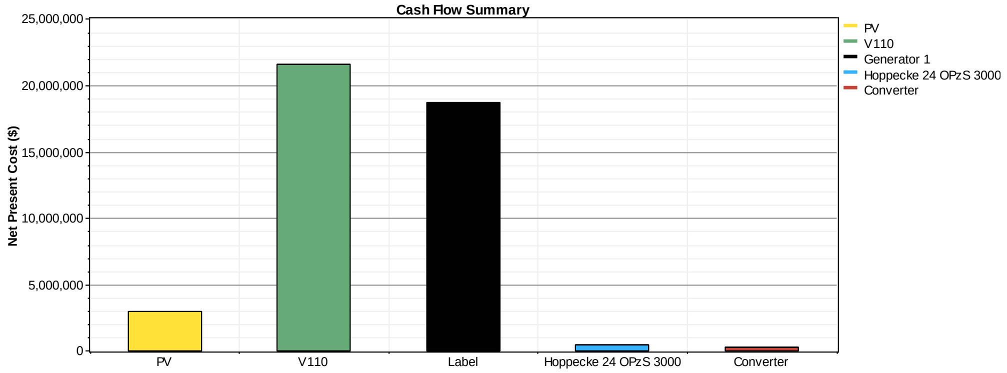


Image 59: Cash flow summary

The cost structure is dominated by the wind turbine and the diesel genset. The battery constitutes only little more than 1 % of the costs. The salvage of the wind turbine saves a pretty high amount of cost as the wind turbines are designed for 15 years and therefore after 25 years could still produce very cheap power for 5 years.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	2,000,000	0	976,173	0	0	2,976,173
V110	13,860,000	7,430,150	2,342,815	0	-2,031,771	21,601,196
Generator 1	0	139,463	900,813	17,701,064	-76,409	18,664,928
Hoppecke 24 OPzS 3000	144,000	326,952	46,856	0	-46,572	471,236
Converter	133,000	89,162	39,047	0	-24,381	236,827
System	16,137,000	7,985,726	4,305,704	17,701,064	-2,179,133	43,950,364

Table 21: Cost structure

This system yields a rather low LCOE of 0.246 $/ kWh. This could have been expected as the diesel gensets stopped running constantly at 30 % of their nominal power to provide the spinning reserve, to run only when the renewable resource was unavailable.

If no pv modules were installed the NPC would increase by $2 million which speaks in favour of combining different generation technologies even though the excess energy is already substantial.

The comparison of the flywheel scenario and the small lead battery scenario demonstrate that the batteries are to prefer in all cases. The CAPEX and the NPC are lower and the renewable energy penetration with 72 %, 6 % higher. Nevertheless, as mentioned before the accuracy of the flywheel model has to be confirmed as the minute variation is not taken into account. Adding pv modules to the flywheel scenario would also enhance its performance. But there is an optimum pv power. Putting 1.3 MW or 500 kW instead of the proposed 1 MW would increase the NPC a little. This shows that depending on the location many variations can occur depending on the wind and solar resource. Lowering the battery capacity to 288 kWh would still be acceptable for the spinning reserve. Even though this would be bring a $1 million smaller CAPEX it would lead to a NPC increase of $2 million. So, here as well the operator has different choices depending on its preferences.

5.3.3 High penetration

In these scenarios with more storage a hybridization of the generation is chosen for both. This measure is applied in order to decrease the storage need given that the generation will be more distributed in time. This derives from the appearance of the wind and solar resource at different times.

The storage capacity is used to equalize the discrepancy between the time of production and consumption of energy. During high production hours exceeding the demand the batteries are charged and during low production discharged.
A techno-economic optimization of the battery capacity leads to different hours of storage depending on the demand and the energy resource.

According to *Younicos*, for a battery with a peak power corresponding to the demand's peak power, 4 hours of energy storage is the economical optimum and these are sufficient for a 65 % of renewable energy penetration in an average island system. [6]

The number of no-sun days defines the percentage of renewable energy consumed as the more no-sun days in a row, the more the diesel genset has to be used.

For the scenarios with more battery capacity, bidirectional converters are used to charge and discharge the electricity in and from the batteries.
The converter power has to match the power difference between the maximal generation of renewable power and the peak load. If it is lower the excess energy would be lost. If the battery SOC is already at its highest point than the energy is lost anyway.

5.3.3.1 Large lead

- PV modules
- Wind turbines
- large capacity lead acid batteries
- Diesel gensets

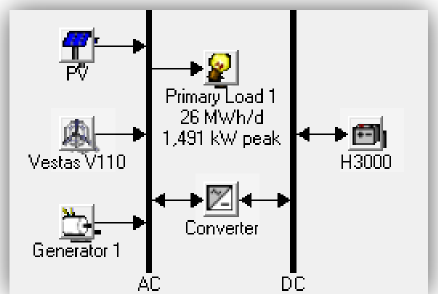


Image 60: Large lead acid battery system diagram

The energy produced by the wind turbines (*Vestas* V110) and the photovoltaic modules with integrated string inverter (PV) is always used to cover the loads. The short term grid stabilization and hour-range storage is achieved thanks to the lead acid battery (H3000). When there is no renewable resource and the battery is depleted the genset takes over (generator 1).

The composition of the generation is nearly identical to the small lead acid battery scenario except the genset power that is increased by 200 kW. A 1 MW PV power is added. The lead acid batteries capacity is risen to 11.52 MWh corresponding to almost 15 times more the capacity of the small lead acid battery scenario. This capacity is not all usable capacity as it is optimized according to DOD levels for prolonging the lifetime as much as possible. The converter size is much higher than in the medium penetration scenarios as the energy flows from and to the battery are much larger.

PV	V110	Label	*Hoppecke* 24 OPzS 3000	Converter
MW	2 MW/unit	MW	Nominal capacity MWh	MW
1	2	1	11.52	1

Table 22: Installed power of the components

The genset production is again decreased allowing to reach a renewable energy fraction of 86 %.

PV Production	Wind Production	Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction
kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr	
1,478,568	13,150,492	1,973,086	16,602,146	9,321,119	0.86

Table 23: Energy production of installed components

It can be seen that the genset is constantly running in May and has many days where it operates 24 hours and fewer days where it just operates for a few hours. This leads to the conclusion that only a seasonal storage solution would allow to increase the renewable fraction without letting the cost skyrocket.

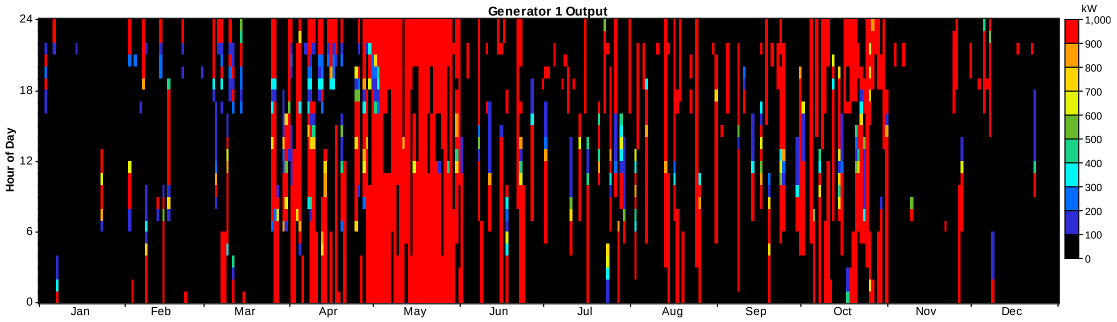


Image 61: Genset production throughout the year

Most of the time the battery's SOC stays at 100 %. It only reached critical values during the months of April, May and October for several days in a row. This shows that the renewable energy resources is unavailable for too many days to recharge the batteries in that period.

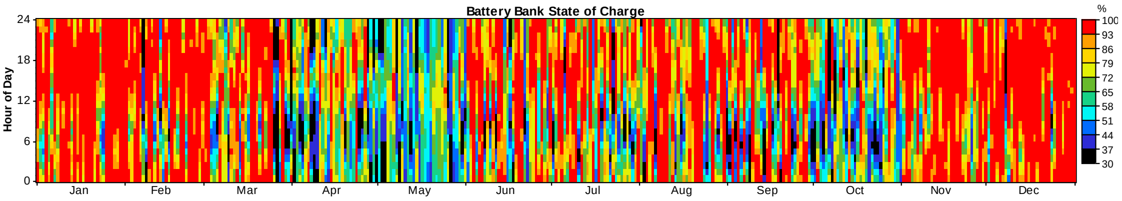


Image 62: Lead acid batteries cycles throughout the year

The excess electricity is rather high but more than 1 GWh lower than the medium penetration scenarios. The unmet load is pretty low with only 6 MWh, or less than a day's demand.

Cap. Shortage	Unmet Load	Excess Electricity
kWh/yr	kWh/yr	kWh/yr
6,09	6,09	6,607,861

Table 24: Unmet and excess energy

Although the battery capacity is high, the impact on the cost is a third than the one of the diesel genset and even less than 4 times the biggest cost factor, the wind turbines. The accumulated cost of the pv and converter is less than 10 % of the total cost.

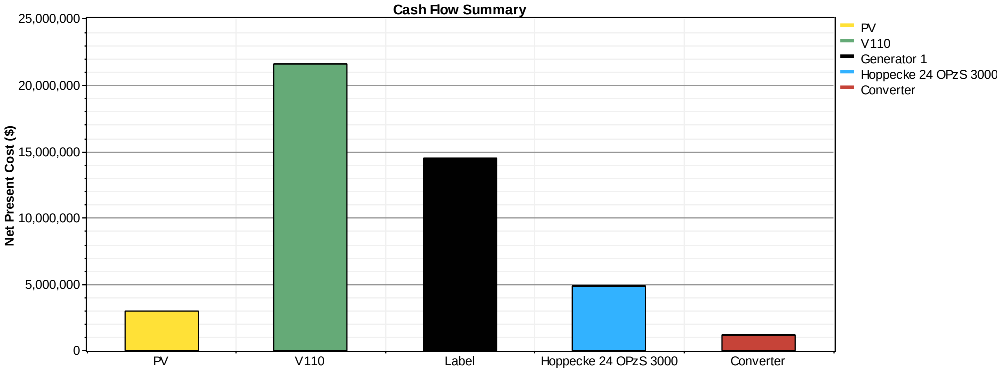


Image 63: Cash flow summary

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	2,000,000	0	976,173	0	0	2,976,173
V110	13,860,000	7,430,150	2,342,815	0	-2,031,771	21,601,196
Generator 1	0	0	653,06	13,900,150	-31,021	14,522,187
Hoppecke 24 OPzS 3000	2,304,000	1,794,497	749,701	0	-26,854	4,821,344
Converter	665,000	445,809	195,235	0	-121,906	1,184,137
System	18,829,000	9,670,455	4,916,984	13,900,150	-2,211,552	45,105,024

Table 25: Cost structure

This system yields a LCOE of 0.248 $/ kWh, slightly higher than the small lead acid batteries scenario (small lead acid battery has 0.246 $ / kWh). This is due to the high cost of the batteries that compensate the decreased fuel consumption. Further, the excess energy is still considerable which illustrates that a downsizing of the generation power might decrease the cost. If an operator is not looking to increase the renewable energy share than the benefit of having the same costs of OPEX to CAPEX will let them choose the smaller battery capacity if he cannot change the generation power.

In the scenarios with large storage, two wind turbines start to make more sense as the excess power is not lost but can be stored and used in times without wind resource. There is an economic optimization between the amount of generation power, storage and diesel genset costs.

5.3.3.2 VRB

- PV modules
- Wind turbines
- large capacity VRB
- Diesel gensets

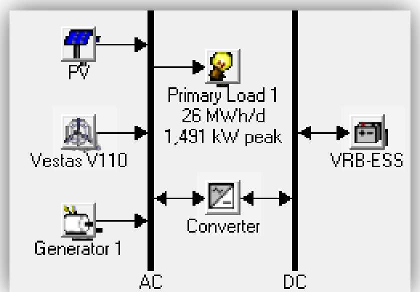


Image 64: VRB system diagram

The energy produced by the wind turbines (*Vestas* V110) and the photovoltaic modules with integrated string inverter (PV) is always used to cover the loads. The short term stabilization and hour-range storage is achieved thanks to the Vanadium redox flow battery (VRB-ESS). When there is no renewable resource and the battery is depleted the genset takes over (generator 1).

PV	V110	Label	VRB-ESS Flow Battery Power	VRB-ESS Flow Battery Storage	Converter
kW	2 MW/unit	kW	MW	MWh	MW
700	2	800	1.5	4	1.5

Table 26: Resulting power of installed components

The PV power allows to produce a little bit more than the strictly needed daily load. It leads to an excess power but also to power resource in periods where no wind is available. The genset does not have to exceed 800 kW as the big demand loads are either covered by the batteries or the renewable energy sources directly.

The resulting capacity rating show that the batteries have ideally an autonomy of only a few hours. The power demonstrates that they are also not designed to absorb all of the renewable energies' power as this would lead to a need of at least 5 MW. The converter has the same power as the batteries which makes sense as if it had a different power it would either lead to a loss of power from renewables that could not be used to charge the battery or to an unused additional converter power.

From the diagram of the monthly average electric production a large dominance of the wind power production throughout the year except for the month of May can be seen. The pv power stays more or less constant. The diesel genset operates especially in May, April and October and the rest of the time stays either very low or does not operate at all.

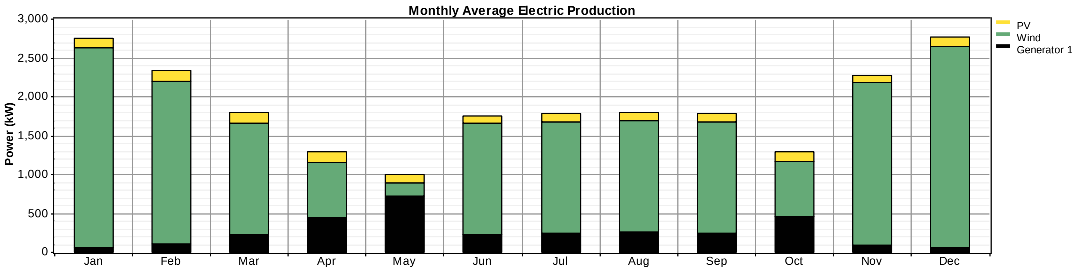


Image 65: Monthly average electric production

As the diagram of the battery bank state of charge reveals with the red color, most of the time the battery has a 100 % SOC. May and in a minor way October are the critical months where it is mostly dark blue or around 0 %.

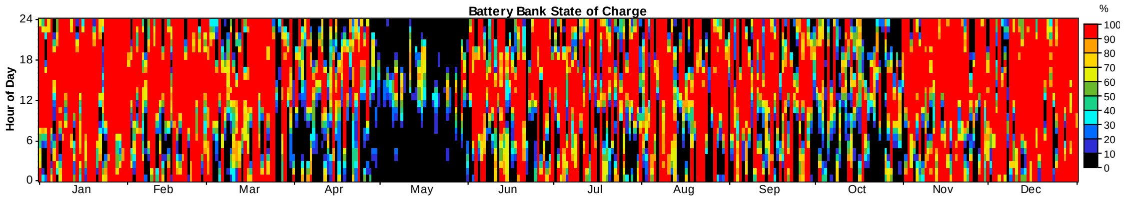


Image 66: VRB production throughout the year

As could have been expected from the diagram above, the diesel genset operates the most and at its highest power when the battery is at the lowest SOC in May and October and the rest of the Months and hours stays idle.

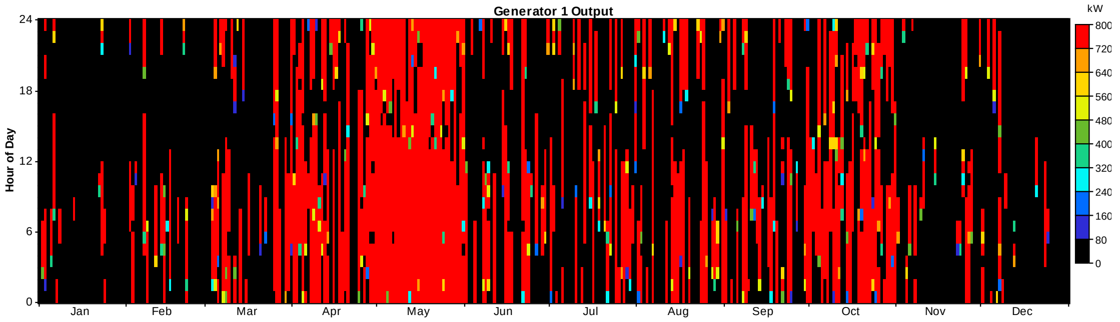


Image 67: Label production throughout the year

The conclusion of both diagrams is that more battery capacity which is expensive would not lead to a big change in renewable energy share as the renewable energy source is simply unavailable for a too long time in just a specific month. It could thus be that a seasonal storage such as a hydrogen system is a reasonable solution.

PV Production	Wind Production	Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction
kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr	
1,035,753	13,156,002	2,326,802	16,518,556	9,131,586	0.75

Table 27: Energy production of installed components

Cap. Shortage	Unmet Load	Excess Electricity
kWh/yr	kWh/yr	kWh/yr
195,621	195,621	6,785,736

Table 28: Unmet and excess energy

There is an almost 6 days unmet load and capacity shortage. The excess electricity is substantial as well with roughly 7 GWh out of 17 GWh mainly renewable energy production. These factors all reflect the high cost of storage and diesel as it is cheaper to lose energy or to not cover the demand until the allowable point than to install more storage.

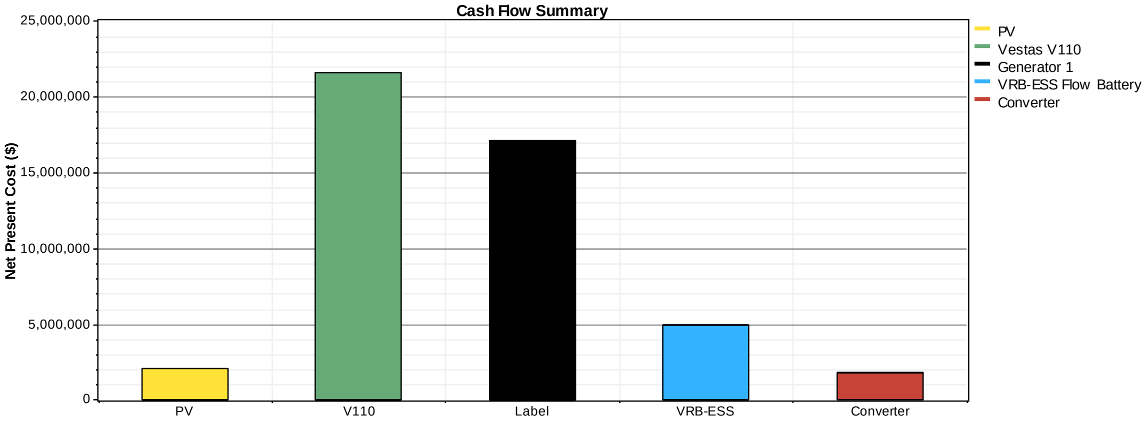


Image 68: Cash flow summary

The wind turbines represent the highest NPC share as they have a high capital cost and have to be replaced after 15 years. The diesel genset with its still present high cost of diesel is second and the batteries close after are on the third position.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	1,400,000	0	683,321	0	0	2,083,321
Vestas V110	13,860,000	7,430,150	2,342,815	0	-2,031,771	21,601,196
Generator 1	0	130,038	754,387	16,303,005	-103,62	17,083,810
VRB-ESS Flow Battery	6,750,000	557,261	700,709	0	-3,078,133	4,929,838
Converter	997,5	668,713	292,852	0	-182,859	1,776,206
System	23,007,500	8,786,162	4,774,084	16,303,005	-5,396,383	47,474,360

Table 29: Cost structure

On the CAPEX side the batteries dominate in the first year but as the replacement cost of the wind turbine is much higher they lose the position again to the wind turbine. Most of the O&M cost derive from the genset but the maintenance of offshore wind turbines is also costly.

This system yields a LCOE of 0.266 $/ kWh losing by 0.02 $ / kWh to the large lead acid battery case.

The stack lifetime is presumed to be only 15 years in HOMER. This might be an issue for the scenario comparison as many manufacturers guarantee 20 years which would decrease the cost of the battery.

5.3.4 100 % renewable energy system

5.3.4.1 Hydrogen

100 % energy consumption via renewables will be achieved with the following composition.

- PV power
- Wind power
- Lead acid battery / VRB capacity
- Electrolyser
- Fuel cell
- h2 tank

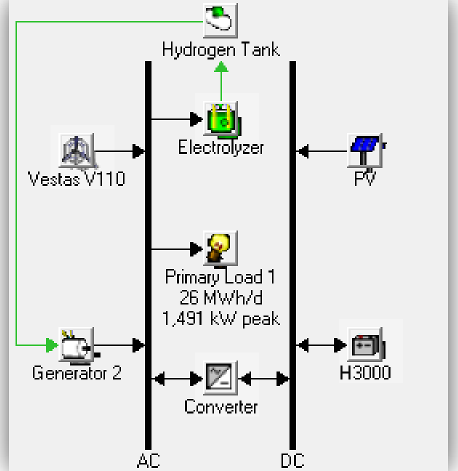


Image 69: Hydrogen system diagram

As no diesel gensets are used as backup, an optimization between the renewable energy share, the battery autonomy and the hydrogen coverage has to be done. The batteries are used for the daily load leveling and the hydrogen for the seasonal variation.

The hydrogen is produced in the electrolyser when the batteries are full and the renewable energy generation is exceeding the demand. It is stored in the hydrogen tank for as long as needed. In times without renewable energy generation and once the battery has reached its lowest allowed SOC, the fuel cell (here generator 2) is activated. The fuel cell is used to recharge the batteries. The power has to be enough to recharge the batteries in a continuous period of a few days and cover the load. The peak power can be much less than the load as it passes through the batteries.

The operating reserve is provided by the batteries.

With 5 MW, the largest power of all scenarios of PV modules is installed. The same is valid for the batteries with an installed capacity of 18.72 MWh. This clear increase is due to the unavailability of a genset that could be ramped up at any moment if diesel is present. This creates the need to have a larger backup in form of a larger generation, larger battery capacity and foremost a hydrogen system storing 4000 kg of hydrogen, the equivalent of 157 hours of autonomy in a tank. The fuel cell is called "label".

PV	V110	Label	*Hoppecke* 24 OPzS 3000	Converter	Electrolyzer	H2 Tank
MW	2 MW/unit	kW	MWh	MW	kW	kg
5	2	200	18.72	2	250	4000

Table 30: Power of installed components

The renewable energy fraction is 1 as all of the energy comes at first in form of wind and sun. The fuel cell serves 126 MWh and the electrolyser 588 MWh. The difference is due to the low efficiencies of the hydrogen system. The very high total electrical production of 20 GWh leads to half of the amount being excess energy.

PV Production	Wind Production	Label Production	Tot. Electrical Production	AC Primary Load Served	Electrolyzer Load Served	Ren. Fraction
kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr	
7,392,825	13,150,492	126,628	20,669,944	9,131,454	588,923	1.00

Table 31: Energy production of installed components

Cap. Shortage	Unmet Load	Excess Electricity
kWh/yr	kWh/yr	kWh/yr
195,757	195,757	10,047,172

Table 32: Unmet and excess energy

The battery capacity varies in a very similar manner as in the other scenarios except that in the periods with high renewable energy resource such as January and December the battery never reaches values lower than 50 %.

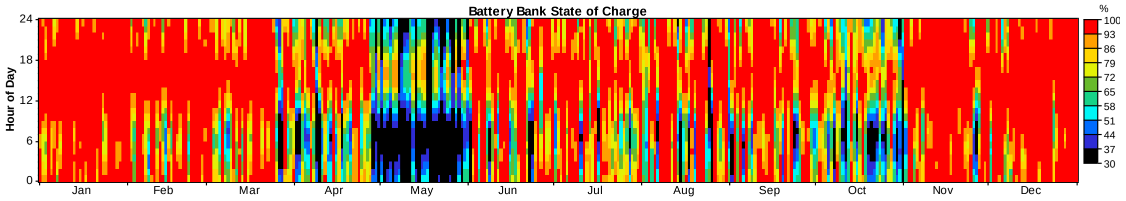


Image 70: Battery cycles

The fuel cell mostly operates in the most critical months for the battery capacity May and October. It is never turned on in the months with a high renewable energy resource. This is sensible as it has a lower efficiency than the battery and hence if the energy can be stored for a short period it is only done via batteries.

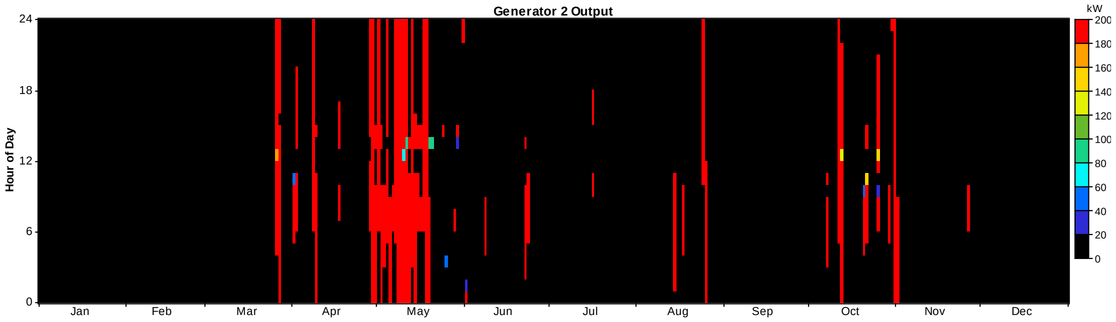


Image 71: Fuel cell production

The h2 tank basically never changes its state in a day. It needs time to consume the stored hydrogen. For instance during the months of February and March it stays at full capacity where as in May it reaches its lowest point.

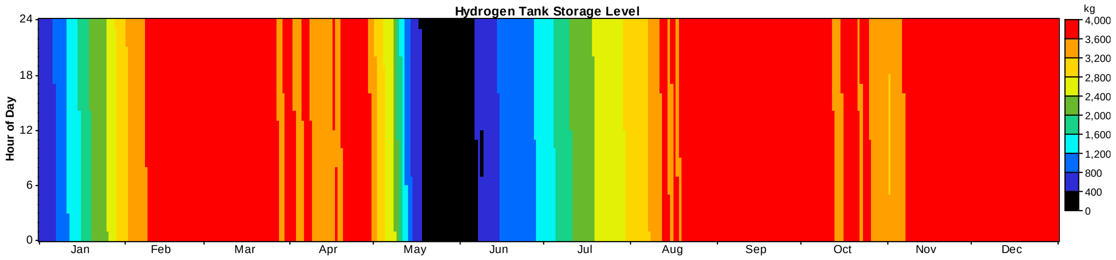


Image 72: h2 tank storage level

The electrolyser mostly works in January when the renewable energy resource is high and the tank starts with 10 % of its maximal charge. It stops producing when the tank is full and starts to produce substantially after a period of large hydrogen usage such as in May.

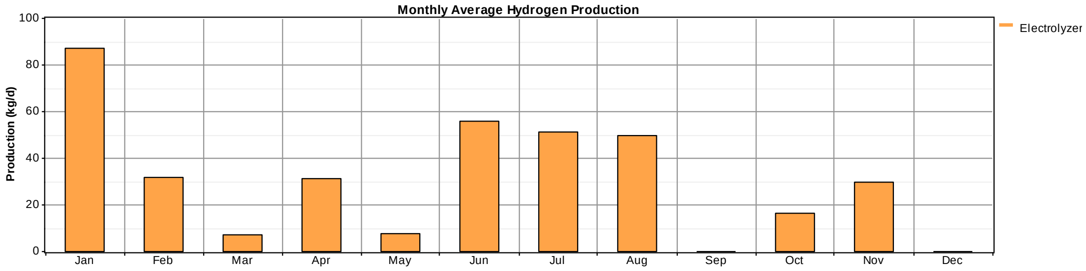


Image 73: Monthly average hydrogen production

The wind turbines lead the costs with over $20 million closely followed by the augmented PV power costing $15 million. The low cost of the lead acid batteries is again reflected in this scenario as the capacity has almost doubled but the price is still a third lower than the wind turbines' one. The hydrogen system has low power ratings which leaves its cost at roughly 10 % of the total costs.

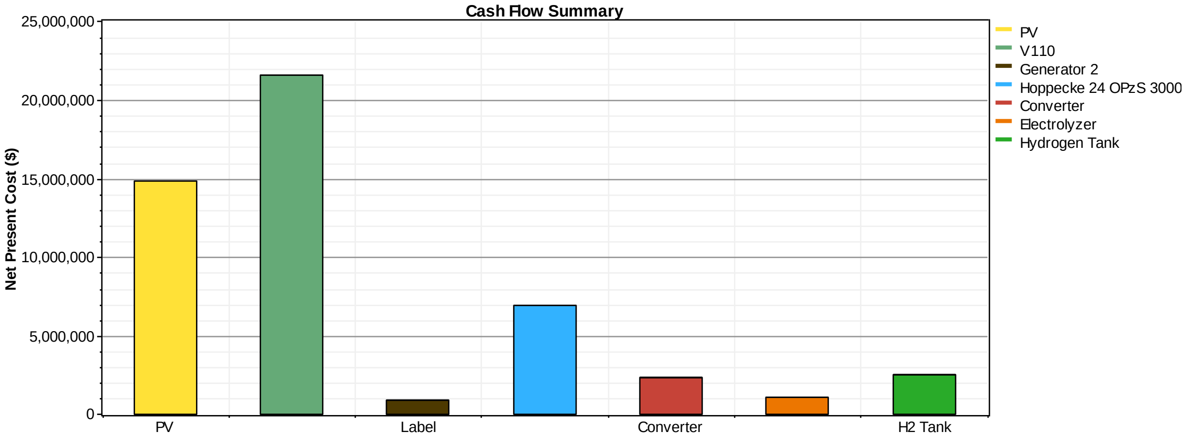


Image 74: Cash flow summary

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	10,000,000	0	4,880,866	0	0	14,880,866
V110	13,860,000	7,430,150	2,342,815	0	-2,031,771	21,601,196
Generator 2	1,020,000	0	3,733	0	-126,417	897,316
Hoppecke 24 OPzS 3000	3,744,000	2,767,245	1,218,264	0	-826,916	6,902,594
Converter	1,330,000	891,618	390,47	0	-243,812	2,368,275
Electrolyzer	1,025,000	0	97,617	0	0	1,122,617
Hydrogen Tank	2,675,000	0	488,09	0	0	3,163,087
System	33,654,000	11,089,012	9,421,849	0	-3,228,916	50,935,952

Table 33: Cost structure

This system yields a LCOE of 0.282 $/ kWh. Considering a $33 million CAPEX, over 2 times the amount of the small lead acid batteries scenario, the operator has here as well to choose between a green system composed of 100 % renewable energies and probably cheaper on the long run considering rising fuel prices or a very low CAPEX and also $7 million lower NPC with a medium penetration system.

Talking about the pathway of the island towards a 100 % renewable energy consumption, it can be seen that once a high penetration is already reached with a large capacity of batteries and diesel gensets as backup most of the needed system to get to 100 % is already present. The missing components consisting in hydrogen tank, electrolyser and fuel cell can be bought with an investment of roughly $5 million. Nonetheless additional PV power and battery capacity should be considered as well which leads to an extra $12 million and $2 million respectively. These extra $19 million compensate for the $17 millions of the diesel system.

6 Conclusion

6.1 Summary of the work

The introduction clearly pointed out the motivation of the work by indicating the multitude of countries still suffering of high electricity prices due to their high diesel share in the electricity generation. This problem will only be exacerbated more in the future. The solution with renewable energies in form of solar power and batteries was shown to become cheaper and more beneficial in many other aspects such as energy security and environmental friendliness. The crucial role of grid stabilization and energy storage and their positive development for the deployment of the renewable energies was underlined.

That was the reason why different microgrid technologies were studied. A distinction between generation, energy flow management, grid stabilization and energy storage solutions was made.

The advantages and disadvantages of solar PV, wind power and diesel gensets were displayed. Modularity for PV, high capacity factor for wind and flexibility for diesel were the advantages and low flexibility for pv, difficult transport for wind and high cost for diesel were the main disadvantages.

Afterwards, the different kinds of converters were shown. The bidirectional converter, always necessary in the presence of energy storage systems, and the grid forming converter, indispensable if a grid has to be created without the aid of a diesel genset were presented.

Companies such as *Younicos* or *SMA* were introduced as leading energy management system or inverters providers.

Then, a special focus put on flywheels with implemented projects of *ABB* and energy storage systems with examples of *SAFT* or *ABB* for grid stabilization yielded results on the different pros and cons of each solution.

Finally, the analysis of the long term energy storage solutions consisting of different battery technologies, lead acid batteries, lithium ion batteries, high temperature batteries and redox flow batteries had as a result e.g. that lithium ion batteries are better equipped for power applications than redox flow batteries and that often the combination of several batteries technologies is considered a good choice. A hydrogen system was also illustrated as a seasonal solution for reaching more than 88 % of renewable energy penetration.

The islands given as references were analysed carefully and the most up-to-date data was searched. Very recent examples as "El Hierro" that was commissioned in June 2014 accentuate this fact. Islands with already a high penetration of renewables have been able to do so often with financial help. All the islands relied on diesel or HFO (heavy fuel oil) before undertaking the renewable energy pathway. Different solutions were found. Tokelau was in evidence with a combination of solar power and lead acid batteries. Graciosa, showcased a mixed of PV, wind, diesel gensets and NaS, lithium ion batteries as storage. El Hierro combined wind power and pumped hydropower as storage. Many more attracted the attention with ambitious plans such as Tonga or La Reunion.

The case study's island presented some interesting facts. It is almost exclusively reliant on diesel gensets but the Government's intention is to become a green island for improving its attractiveness for tourists and its inhabitants. It has already been decided to commission two 2 MW wind offshore turbines, a very particular situation as very few offshore wind plants have been installed in developing countries up to today. This will radically transform the energy situation of the island enabling it to become environmentally friendly and to guarantee low energy prices in the future. It is a very big project with a very high power considering that the current peak power of the island is 1500 kW.

Afterwards, the software HOMER was explained as tool for making techno-economic calculations in microgrids consisting of different technologies.

The main economical and technical assumptions were enumerated. Then, the scenarios distinguished depending on the penetration level, low, medium, high or 100 % renewable energies were simulated. The results were analysed and discussed.

The most expensive scenario was the only diesel genset scenario with a NPC of $72 million. The low penetration scenario with wind turbines gave a surprisingly high percentage of 51 % thanks to its oversized 4 MW wind turbines. These oversized turbines were seen as a precaution to avoid extra installation costs of an extra wind turbine for a possible future increase in demand. Even though the investment cost is much lower in the pv scenario than in the wind turbines scenario, the NPC is bigger than the case with 1 wind turbine and equal to the case with 2 wind turbines.

The medium penetration scenarios both already enabled a penetration around 70 %. The small lead acid battery scenario was to prefer to the flywheel scenario as it offered a better NPC, CAPEX and a renewable energy penetration.

The high penetration scenarios both allowed to reach a penetration of around 85 %. Although they achieve almost the same results, the VRB seem to be still too expensive in comparison to the lead acid batteries. Especially, the higher upfront cost have to come down as it would be a big barrier for the adoption of this technology in these locations.

The 100 % renewable energy scenario emphasizes that the economic feasibility is not far. A much higher generation power and battery capacity have to accompany the hydrogen system. The investment cost corresponds more or less to the total cost of the diesel genset. As a consequence, if prices of the components go down, there will be a business case.

A very interesting observation was that the low penetration scenarios had a very similar NPC of around $70 million. The only genset scenario revealed a slightly higher NPC but in compensation had an advantage comparing the CAPEX. All the other scenarios with a higher penetration were having a NPC from $44 to $51 million with a clear pole position of the small lead scenario and a last position of the flywheel and hydrogen scenario. This implies that the decision making in the future will become more and more complicated but interesting. Regional factors and technological trends will have to be analysed closely when making strategic decisions for the own energy sector.

It has to be stated that the quality of the results highly depends on the quality of the available data. The fact for example, that only one day's demand was given and the rest of the yearly demand had to be extrapolated emphasizes the importance of the statement.

6.2 Give recommendations

In the following a presentation of a possible pathway from only gensets towards a 100 % renewable energies.

First, 1 wind turbine would be installed and the diesel-wind system would be controlled by a microgrid controller yielding a 40-50 % renewable energy penetration .

In a second step, a small PV power and a small capacity of lead acid batteries allowing to avoid the obligatory spinning reserve of the gensets would raise the renewable penetration to around 70 %.

In a third step, the battery capacity and the PV power would be increased to reach 85 % penetration.

Finally, a hydrogen system would completely substitute the remaining diesel genset in order to achieve 100 % renewable energies.

6.3 Future prospects

With an algorithm able to study more dynamic situation and with better availability of data the analysis could be improved further.

The use of the hydrogen solution might become more viable if the efficiency is increased. In other words, if the heat that is lost in the current model in the PEM could be used. A Solid oxide fuel cell might be more effective in this case which would allow to lower costs and increase the efficiency to 80-85%. [90]

In order to make better decisions, in the future it would also be useful to study:

- Sensitivities with all the variables, especially the diesel price as it will be rising in the future most probably.
- A power flow analysis to judge which generation technologies would cause more losses in the grid.
- A comparison of the impact of a central model with big components or distributed model on the different scenarios.
- A demand side management enabling the reduction of generation or storage.

My personal view on the prospects of the island and MW-scale locations in general is that inevitably more locations will take measures to counteract the high and ever increasing cost of fossil fuels. This will convince larger countries of the possibility of a large penetration of renewables and the benefits of implementing grid stabilization and energy storage solutions.

A good analogy can be made with the telecommunication sector for developing countries. Few years ago, telecommunication was unavailable in many developing countries especially in Africa. As building up a system based on cables such as in the early beginnings in Europe was more expensive than building telecommunication towers the latter option was chosen. The expansion of this more efficient and more modern solution was rapid which nowadays allows almost every African to use a mobile phone.

In the case of the energy sector, at first large power plants were built and cables brought the energy to the consumer over long distances. But it is often more economic and simpler to build local microgrids using local renewable energy resources allowing a rapid expansion and the widespread use of clean energy.

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Annexes

Data results of scenarios

Only genset

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generator 1	0	771,545	3,591,535	68,388,656	-185,907	72,565,816
System	0	771,545	3,591,535	68,388,656	-185,907	72,565,816
	V110	Label	Total Capital Cost	Total NPC	Tot. Ann. Cap. Cost	Tot. Ann. Repl. Cost
#		kW	$	$	$/yr	$/yr
2	0	1,4	0	72,565,800	0	29,997
Total O&M Cost	Total Fuel Cost	Total Ann. Cost	Operating Cost	COE	Wind Production	
$/yr	$/yr	$/yr	$/yr	$/kWh	kWh/yr	
183,96	3,502,896	3,716,852	3,716,852	0.400	0	
Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction	Cap. Shortage		
kWh/yr	kWh/yr	kWh/yr		kWh/yr		
9,293,995	9,293,995	9,293,995	0.00	33,215		
Unmet Load	Excess Electricity	Diesel	Label Fuel	Label Hours	Label Starts	Label Life
kWh/yr	kWh/yr	L/yr	L/yr	hr/yr	starts/yr	yr
33,215	0	3,304,619	3,304,619	8,76	1	7.99

PV

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	3,000,000	0	1,464,260	0	0	4,464,260
Generator 1	0	826,655	3,848,074	60,817,584	-199,186	65,293,128
System	3,000,000	826,655	5,312,334	60,817,584	-199,186	69,757,384
PV	Label	Total Capital Cost	Total NPC	Tot. Ann. Cap. Cost	Tot. Ann. Repl. Cost	Total O&M Cost
kW	kW	$	$	$/yr	$/yr	$/yr
1,5	1,5	3,000,000	69,757,360	153,661	32,139	272,1
Total Fuel Cost	Total Ann. Cost	Operating Cost	COE	PV Production	Label Production	
$/yr	$/yr	$/yr	$/kWh	kWh/yr	kWh/yr	
3,115,102	3,573,003	3,419,342	0.383	2,219,476	7,550,325	
Tot. Electrical Production	AC Primary Load Served	Ren. Fraction	Cap. Shortage	Unmet Load		
kWh/yr	kWh/yr		kWh/yr	kWh/yr		
9,769,800	9,327,210	0.23	0	0		
Excess Electricity	Diesel	Label Fuel	Label Hours	Label Starts	Label Life	
kWh/yr	L/yr	L/yr	hr/yr	starts/yr	yr	
442,571	2,938,776	2,938,776	8,76	1	7.99	

Wind

V110	Label	Total Capital Cost	Total NPC	Tot. Ann. Cap. Cost	Tot. Ann. Repl. Cost
2 MW/unit	MW	$	$	$/yr	$/yr
1	1.4	6,930,000	61,957,072	354,958	168,25
1	1,45	6,930,000	63,177,128	354,958	169,322
1	1,5	6,930,000	64,404,444	354,958	170,393
2	1.4	13,860,000	69,747,648	709,915	306,504
2	1,45	13,860,000	71,129,680	709,915	307,575
2	1,5	13,860,000	72,514,672	709,915	308,647
0	1,4	0	72,565,800	0	29,997
0	1,45	0	73,534,552	0	31,068
0	1,5	0	74,486,312	0	32,139
Total O&M Cost	Total Fuel Cost	Total Ann. Cost	Operating Cost	COE	Wind Production
$/yr	$/yr	$/yr	$/yr	$/kWh	kWh/yr
243,96	2,406,301	3,173,469	2,818,511	0.340	6,575,064
250,53	2,461,151	3,235,960	2,881,003	0.347	6,575,064
257,1	2,516,374	3,298,824	2,943,866	0.354	6,575,064
303,96	2,252,126	3,572,505	2,862,590	0.383	13,150,128
310,53	2,315,273	3,643,294	2,933,378	0.391	13,150,128
317,1	2,378,572	3,714,234	3,004,318	0.398	13,150,128
183,96	3,502,896	3,716,852	3,716,852	0.400	0
190,53	3,544,874	3,766,472	3,766,472	0.404	0
197,1	3,585,983	3,815,222	3,815,222	0.409	0
Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction	Cap. Shortage	
kWh/yr	kWh/yr	kWh/yr		kWh/yr	
5,155,897	11,730,960	9,325,799	0.56	33,215	
5,222,717	11,797,781	9,326,664	0.56	14,965	
5,290,948	11,866,012	9,327,210	0.55	0	
4,574,114	17,724,242	9,325,984	0.74	33,215	
4,672,244	17,822,372	9,326,734	0.74	14,965	
4,770,947	17,921,074	9,327,210	0.73	0	
9,293,995	9,293,995	9,293,995	0.00	33,215	
9,312,245	9,312,245	9,312,245	0.00	14,965	
9,327,210	9,327,210	9,327,210	0.00	0	

Wind

Unmet Load	Unmet Load Frac.	Excess Electricity	Diesel	Label Fuel	Label Hours
kWh/yr		kWh/yr	L/yr	L/yr	hr/yr
1,411	0.00	2,405,166	2,270,095	2,270,095	8,76
546	0.00	2,471,124	2,321,841	2,321,841	8,76
0	0.00	2,538,808	2,373,938	2,373,938	8,76
1,226	0.00	8,398,280	2,124,647	2,124,647	8,76
476	0.00	8,495,661	2,184,220	2,184,220	8,76
0	0.00	8,593,894	2,243,936	2,243,936	8,76
33,215	0.00	0	3,304,619	3,304,619	8,76
14,965	0.00	0	3,344,221	3,344,221	8,76
0	0.00	0	3,383,003	3,383,003	8,76
Label Starts	Label Life				
starts/yr	yr				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction	Cap. Shortage	
kWh/yr	kWh/yr	kWh/yr		kWh/yr	
5,155,897	11,730,960	9,325,799	0.56	33,215	
5,222,717	11,797,781	9,326,664	0.56	14,965	
5,290,948	11,866,012	9,327,210	0.55	0	
4,574,114	17,724,242	9,325,984	0.74	33,215	
4,672,244	17,822,372	9,326,734	0.74	14,965	
4,770,947	17,921,074	9,327,210	0.73	0	
9,293,995	9,293,995	9,293,995	0.00	33,215	
9,312,245	9,312,245	9,312,245	0.00	14,965	
9,327,210	9,327,210	9,327,210	0.00	0	
Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)
V110	13,860,000	7,430,150	2,342,815	0	-2,031,771
Generator 1	0	771,545	3,591,535	43,969,292	-185,907
System	13,860,000	8,201,694	5,934,351	43,969,292	-2,217,678
Total ($)					
21,601,196					
48,146,468					
69,747,656					

flywheel

V110	Label	Total Capital Cost	Total NPC	Tot. Ann. Cap. Cost	Tot. Ann. Repl. Cost
2 MW/unit	MW	$	$	$/yr	$/yr
1	1.4	6,930,000	61,957,072	354,958	168,25
1	1,45	6,930,000	63,177,128	354,958	169,322
1	1,5	6,930,000	64,404,444	354,958	170,393
2	1.4	13,860,000	69,747,648	709,915	306,504
2	1,45	13,860,000	71,129,680	709,915	307,575
2	1,5	13,860,000	72,514,672	709,915	308,647
0	1,4	0	72,565,800	0	29,997
0	1,45	0	73,534,552	0	31,068
0	1,5	0	74,486,312	0	32,139
Total O&M Cost	Total Fuel Cost	Total Ann. Cost	Operating Cost	COE	Wind Production
$/yr	$/yr	$/yr	$/yr	$/kWh	kWh/yr
243,96	2,406,301	3,173,469	2,818,511	0.340	6,575,064
250,53	2,461,151	3,235,960	2,881,003	0.347	6,575,064
257,1	2,516,374	3,298,824	2,943,866	0.354	6,575,064
303,96	2,252,126	3,572,505	2,862,590	0.383	13,150,128
310,53	2,315,273	3,643,294	2,933,378	0.391	13,150,128
317,1	2,378,572	3,714,234	3,004,318	0.398	13,150,128
183,96	3,502,896	3,716,852	3,716,852	0.400	0
190,53	3,544,874	3,766,472	3,766,472	0.404	0
197,1	3,585,983	3,815,222	3,815,222	0.409	0
Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction	Cap. Shortage	
kWh/yr	kWh/yr	kWh/yr		kWh/yr	
5,155,897	11,730,960	9,325,799	0.56	33,215	
5,222,717	11,797,781	9,326,664	0.56	14,965	
5,290,948	11,866,012	9,327,210	0.55	0	
4,574,114	17,724,242	9,325,984	0.74	33,215	
4,672,244	17,822,372	9,326,734	0.74	14,965	
4,770,947	17,921,074	9,327,210	0.73	0	
9,293,995	9,293,995	9,293,995	0.00	33,215	
9,312,245	9,312,245	9,312,245	0.00	14,965	
9,327,210	9,327,210	9,327,210	0.00	0	

flywheel

Unmet Load	Unmet Load Frac.	Excess Electricity	Diesel	Label Fuel	Label Hours
kWh/yr		kWh/yr	L/yr	L/yr	hr/yr
1,411	0.00	2,405,166	2,270,095	2,270,095	8,76
546	0.00	2,471,124	2,321,841	2,321,841	8,76
0	0.00	2,538,808	2,373,938	2,373,938	8,76
1,226	0.00	8,398,280	2,124,647	2,124,647	8,76
476	0.00	8,495,661	2,184,220	2,184,220	8,76
0	0.00	8,593,894	2,243,936	2,243,936	8,76
33,215	0.00	0	3,304,619	3,304,619	8,76
14,965	0.00	0	3,344,221	3,344,221	8,76
0	0.00	0	3,383,003	3,383,003	8,76
Label Starts	Label Life				
starts/yr	yr				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
1	7.99				
Label Production	Tot. Electrical Production	AC Primary Load Served	Ren. Fraction	Cap. Shortage	
kWh/yr	kWh/yr	kWh/yr		kWh/yr	
5,155,897	11,730,960	9,325,799	0.56	33,215	
5,222,717	11,797,781	9,326,664	0.56	14,965	
5,290,948	11,866,012	9,327,210	0.55	0	
4,574,114	17,724,242	9,325,984	0.74	33,215	
4,672,244	17,822,372	9,326,734	0.74	14,965	
4,770,947	17,921,074	9,327,210	0.73	0	
9,293,995	9,293,995	9,293,995	0.00	33,215	
9,312,245	9,312,245	9,312,245	0.00	14,965	
9,327,210	9,327,210	9,327,210	0.00	0	
Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)
V110	13,860,000	7,430,150	2,342,815	0	-2,031,771
Generator 1	0	771,545	3,591,535	43,969,292	-185,907
System	13,860,000	8,201,694	5,934,351	43,969,292	-2,217,678
Total ($)					
21,601,196					
48,146,468					
69,747,656					

Small lead

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	2,000,000	0	976,173	0	0	2,976,173
V110	13,860,000	7,430,150	2,342,815	0	-2,031,771	21,601,196
Generator 1	0	139,463	900,813	17,701,064	-76,409	18,664,928
Hoppecke 24 OPzS 3000	144	326,952	46,856	0	-46,572	471,236
Converter	133	89,162	39,047	0	-24,381	236,827
System	16,137,000	7,985,726	4,305,704	17,701,064	-2,179,133	43,950,364
PV	V110	Label	*Hoppecke* 24 OPzS 3000	Converter	Total Capital Cost	
MW	2 MW/unit	kW	Nominal capacity MWh	kW	$	
1	2	800	720	200	16,137,000	
1,3	2	800	720	200	16,737,000	
500	2	1000	720	300	15,203,500	
1	2	1000	288	100	15,984,100	
Total NPC	Tot. Ann. Cap. Cost	Tot. Ann. Repl. Cost	Total O&M Cost	Total Fuel Cost	Total Ann. Cost	
$	$/yr	$/yr	$/yr	$/yr	$/yr	
43,950,356	826,544	297,416	220,54	906,656	2,251,157	
44,077,276	857,277	296,345	233,884	870,152	2,257,658	
45,442,068	778,73	299,448	203,68	1,045,705	2,327,563	
45,506,712	818,713	284,711	228,195	999,255	2,330,874	
Operating Cost	COE	PV Production	Wind Production	Label Production	Tot. Electrical Production	
$/yr	$/kWh	kWh/yr	kWh/yr	kWh/yr	kWh/yr	
1,424,612	0.246	1,478,568	13,150,492	2,437,024	17,066,084	
1,400,381	0.246	1,922,130	13,150,492	2,334,605	17,407,228	
1,548,833	0.251	739,284	13,150,492	2,809,412	16,699,188	
1,512,161	0.252	1,478,568	13,150,492	2,571,087	17,200,148	

Small lead

AC Primary Load Served	Ren. Fraction	Cap. Shortage	Cap. Shortage Frac.	Unmet Load	Unmet Load Frac.	Excess Electricity
kWh/yr		kWh/yr		kWh/yr		kWh/yr
9,151,266	0.86	175,946	0	175,946	0.02	7,841,149
9,165,455	0.87	161,753	0	161,753	0.02	8,170,533
9,281,168	0.83	46,039	0	46,039	0.00	7,341,984
9,263,297	0.85	63,912	0	63,912	0.01	7,917,979
Label Fuel	Label Hours	Label Starts	Label Life	Battery Autonomy	Battery Throughput	Battery Life
L/yr	hr/yr	starts/yr	yr	hr	kWh/yr	yr
855,336	3,845	547	18.21	0.47	169,795	7.2
820,899	3,707	544	18.88	0.47	164,198	7.5
986,514	3,552	603	19.71	0.47	175,253	7.0
942,694	3,749	612	18.67	0.19	43,546	11.2
Diesel						
L/yr						
855,336						
820,899						
986,514						
942,694						

Large lead

PV	V110	Label	*Hoppecke* 24 OPzS 3000	Converter	Total Capital Cost	Total NPC
MW	2 MW/unit	MW	Nominal capacity MWh	MW	$	$
1	2	1	11.52	1	18,829,000	45,105,032
Tot. Ann. Cap. Cost	Tot. Ann. Repl. Cost	Total O&M Cost	Total Fuel Cost	Total Ann. Cost		
$/yr	$/yr	$/yr	$/yr	$/yr		
964,43	382,048	251,85	711,972	2,310,300		
Operating Cost	COE	PV Production	Wind Production	Label Production	Tot. Electrical Production	
$/yr	$/kWh	kWh/yr	kWh/yr	kWh/yr	kWh/yr	
1,345,870	0.248	1,478,568	13,150,492	1,973,086	16,602,146	
AC Primary Load Served	Ren. Fraction	Cap. Shortage	Cap. Shortage Frac.	Unmet Load	Unmet Load Frac.	Excess Electricity
kWh/yr		kWh/yr		kWh/yr		kWh/yr
9,321,119	0.88	6,09	0	6,09	0.00	6,607,861
Diesel	Label Fuel	Label Hours	Label Starts	Label Life		
L/yr	L/yr	hr/yr	starts/yr	yr		
671,671	671,671	2,23	173	31.39		
Battery Autonomy	Battery Throughput	Battery Life				
hr	kWh/yr	yr				
7.57	1,551,132	12.6				
Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	2,000,000	0	976,173	0	0	2,976,173
V110	13,860,000	7,430,150	2,342,815	0	-2,031,771	21,601,196
Generator 1	0	0	653,06	13,900,150	-31,021	14,522,187
Hoppecke 24 OPzS 3000	2,304,000	1,794,497	749,701	0	-26,854	4,821,344
Converter	665	445,809	195,235	0	-121,906	1,184,137
System	18,829,000	9,670,455	4,916,984	13,900,150	-2,211,552	45,105,024

VRB

PV	V110	Label	VRB-ESS Flow Battery Power	VRB-ESS Flow Battery Storage	Converter	
kW	2 MW/unit	kW	MW	MWh	MW	
700	2	800	1.5	4	1.5	
Total Capital Cost	Total NPC	Tot. Ann. Cap. Cost	Tot. Ann. Repl. Cost	Total O&M Cost	Total Fuel Cost	
$	$	$/yr	$/yr	$/yr	$/yr	
23,007,500	47,474,364	1,178,454	173,626	244,531	835,047	
Total Ann. Cost	Operating Cost	COE	PV Production	Wind Production	Label Production	
$/yr	$/yr	$/kWh	kWh/yr	kWh/yr	kWh/yr	
2,431,658	1,253,204	0.266	1,035,753	13,156,002	2,326,802	
Tot. Electrical Production	AC Primary Load Served	Ren. Fraction	Cap. Shortage	Unmet Load		
kWh/yr	kWh/yr		kWh/yr	kWh/yr		
16,518,556	9,131,586	0.75	195,621	195,621		
Excess Electricity	Diesel	Label Fuel	Label Hours	Label Starts	Label Life	Battery Autonomy
kWh/yr	L/yr	L/yr	hr/yr	starts/yr	yr	hr
6,785,736	787,78	787,78	3,22	196	21.74	3.76
Battery Throughput	Battery Life					
kWh/yr	yr					
1,178,119	15.0					
Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	1,400,000	0	683,321	0	0	2,083,321
Vestas V110	13,860,000	7,430,150	2,342,815	0	-2,031,771	21,601,196
Generator 1	0	130,038	754,387	16,303,005	-103,62	17,083,810
VRB-ESS Flow Battery	6,750,000	557,261	700,709	0	-3,078,133	4,929,838
Converter	997,5	668,713	292,852	0	-182,859	1,776,206
System	23,007,500	8,786,162	4,774,084	16,303,005	-5,396,383	47,474,360

H2

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	10,000,000	0	4,880,866	0	0	14,880,866
V110	13,860,000	7,430,150	2,342,815	0	-2,031,771	21,601,196
Generator 2	1,020,000	0	3,733	0	-126,417	897,316
Hoppecke 24 OPzS 3000	3,744,000	2,767,245	1,218,264	0	-826,916	6,902,594
Converter	1,330,000	891,618	390,469	0	-243,812	2,368,275
Electrolyzer	1,025,000	0	97,617	0	0	1,122,617
Hydrogen Tank	2,675,000	0	488,087	0	0	3,163,087
System	33,654,000	11,089,012	9,421,849	0	-3,228,916	50,935,952
PV	V110	Label	*Hoppecke* 24 OPzS 3000	Converter	Electrolyzer	H2 Tank
MW	2 MW/unit	MW	MWh	MW	kW	kg
5	2	200	3.12	2	250	4000
Total Capital Cost	Total NPC	Tot. Ann. Cap. Cost	Tot. Ann. Repl. Cost			
$	$	$/yr	$/yr			
33,119,000	50,293,952	1,696,370	402,117			
Total O&M Cost	Total Fuel Cost	Total Ann. Cost				
$/yr	$/yr	$/yr				
477,591	0	2,576,078				
Operating Cost	COE	PV Production	Wind Production	Label Production	Tot. Electrical Production	
$/yr	$/kWh	kWh/yr	kWh/yr	kWh/yr	kWh/yr	
879,708	0.282	7,392,825	13,150,492	126,628	20,669,944	
AC Primary Load Served	Electrolyzer Load Served	Ren. Fraction	Cap. Shortage	Unmet Load		
kWh/yr	kWh/yr		kWh/yr	kWh/yr		
9,131,454	588,923	1.00	195,757	195,757		
Excess Electricity	Label Fuel	Label Hours	Label Starts	Label Life		
kWh/yr	kg/yr	hr/yr	starts/yr	yr		
10,047,172	7,598	957	34	31.35		
Battery Autonomy	Battery Throughput	Battery Life				
hr	kWh/yr	yr				
12.31	2,079,336	15.3				

Renewables shares calculated

Total consumption	9327			
Wind				
1 turbine				
Energy wind produced	Energy excess	Energy wind consumed	share wind	
6575	2405	4170	45	
2 turbines				
Energy wind produced	Energy excess	Energy wind consumed	share wind	
13150	8398	4752	51	
large Lead				
Energy wind	Energy pv	Energy excess	consumed energy	share renewables
13150	591	5669	8072	87
small lead				
Energy wind	Energy pv	Energy excess	consumed energy	share renewables
13150	1478	7841	6787	72,76723491
	PV			
PV power	Energy pv produced	Energy excess	Energy pv consumed	share renewables
1500	2219	442	1777	19
2000	2959	950	2009	22

Price of components

cost of tokelau project in Mio. NZD	Cost of tokelau project in Mio. USD	share of inverters	cost of inverters in Mio. USD	installed kW of inverters	Cost in USD per kw	20% cheaper
8,75	7,35	0,14	1,029	1237	831,851253	665,481002
		share of bos				
8,75	7,35	0,05	0,3675	1237	297,089733	267,38076
Atersa module of 240 Wp cost in euro	in $	$ per watt				
148,8	193,44	0,806				
H2 tank						
kwh/nm	kwh/kg	kg/nm	euro/Nm	euro/kg	$/kg	
3	33	11	38	418	535,04	
Assumption due to time difference (early 2013 vs 2015) and bigger inverter 20 % cheaper						

Flywheel cost calculation

beacon Smart energy		kW	total price in $ assuming same kW price as *Powerstore*
25	kwh	100	120000
90	MWs		
Powerstore	kW	price in $	price per kW
	500	600000	1200
16	MWs		

Wind speed calculations

Local weather station at 3 meters sea altitude	Nasa wind data	Average	Rounded
4	**7,98**	**5,99**	**6**
3,3	**6,51**	**4,905**	**5**
2,5	**5,66**	**4,08**	**4**
1,8	**4,04**	**2,92**	**3**
1,5	**3,46**	**2,48**	**2**
2,2	**5,5**	**3,85**	**4**
2,4	**5,44**	**3,92**	**4**
2,9	**6,01**	**4,455**	**4**
2,3	**4,9**	**3,6**	**4**
1,6	**4,24**	**2,92**	**3**
3,1	**6,41**	**4,755**	**5**
4	**8,11**	**6,055**	**6**