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HYBRID POWER GENERATION CONCEPT FOR SMALL GRIDS

Master's Thesis for the degree of Master of Science in Technology submitted for inspection, Vaasa, 10.04.2013.

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PREFACE

This thesis is made for Wärtsilä Finland Oy with the intention of investigating in the feasibility of adding renewable power generation to combustion engine power plants and making it a profitable hybrid power system.

I would like to thank my instructor Mr. Niklas Wägar for finding this subject for me and for supporting me throughout all my time working in Wärtsilä. The thesis subject could not have been more interesting, due to my savour for renewable energy technique and the incremental focus in it nowadays. My gratitude for Mr. Jyrki Leino as well for helping me simulate the results and Professor Timo Vekara for the supervision of this thesis. I found working in Wärtsilä very pleasant but meanwhile comfortably challenging.

I would also like to thank my family and friends for all the support I received during my time as a student in University of Vaasa.

Vaasa, 10.04.2013

Toni Hyytinen

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SYMBOLS AND ABBREVIATIONS

Symbols

α	Thermal voltage timing completion factor
ρ	Air density
ω	Angular speed
A	Area
C_{p}	Heat capacity
D	Thermal diffusivity
H	Inertia constant
I	Current
I_0	Saturation current
I_{L}	Light current
J	Inertia
P	Power
R_{S}	Series resistance
U	Output voltage
V	Speed

Abbreviations

AC	Alternative current
AVR	Automatic voltage regulation
BOS	Balance of system
CAPEX	Capital expenditures
CRO	Crude oil
CSP	Concentrated solar power
DFIG	Double-fed induction generator
DC	Direct current
EMC	Electromagnetic compatibility

FIT	Feed-in tariff
FWE	Fuel-water emulsion
GTO	Gate turn-off thyristor
HFO	Heavy fuel oil
HVAC	High voltage alternative current
IGBT	Insulated gate-bipolar transistor
LBF	Liquid bio fuel
LFO	Light fuel oil
LNG	Liquefied natural gas
MPPT	Maximum power point tracker
OPEX	Operational expenditures
PLC	Programmable logic controller
PMSG	Permanent magnet synchronous generator
PV	Photovoltaic
PWM	Pulse width modulation
SVC	Static VAR compensator
THD	Total harmonic distortion
VAR	Volt ampere reactive
VSC	Voltage source controller
WISE	Wärtsilä Information System Environment
WOIS	Wärtsilä Operator Interface System
WTG	Wind turbine generator

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ABSTRACT

The increasing power consumption and the targets of emissions reduction in the world has lead to further investigations in utilizing renewable energy sources. However, fluctuations in the power generation with renewables occur. Therefore, it is important that the power supply for the grid is reliable in order to avoid shortage of supply.

The aim of this thesis is to study the feasibility of constructing a hybrid power plant consisting of solar and wind power combined with liquid or gas fuelled combustion engines for a small grid. Due to the restriction of small grids, islands and off-grid sites, especially industrial sites, create a perfect location for this hybrid power generation concept. Also, the good weather conditions on islands, especially in the sun-belt area increase the profitability of investing in hybrid power plants. The own consumption of existing power plants is also studied and by adding a CSP system that generates hot water for engine and fuel tank pre-heating, especially for power plants in stand-by mode locating in sunny areas, the efficiency is improved.

The fast starting and load following combustion engines are perfectly fitting together with the fluctuating renewable power generation and thus the stored fuel will work as storage system, responding to power demand very fast.

The main results of this thesis origins from the simulations of the hybrid power plant with both liquid fuel combustion engines and solar and wind power. The proper share of renewable power generation and power generated by engines at a particular time are shown. Payback time calculations for ideal hybrid power generation concepts and for the CSP system for minimizing own consumption are made as well. The results show that hybrid power plants on islands and off-grid solutions are extremely cost-effective, with a payback time of only six years. Thus, investment in hybrid power plants is recommended.

KEYWORDS: Hybrid power plant, renewable energy, island power generation system

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TIIVISTELMÄ

Lisääntyneen sähköntarpeen ja tiukkojen päästövaatimusten takia on uusiutuvien energiamuotojen hyödyntämistä tutkittu yhä enenevissä määrin. Uusiutuvien energiajärjestelmien sähköntuotannon heilahtelut saattavat aiheuttavaa vajauksen kuorman sähkönsaantiin, sekä mahdollisesti ongelmia sähkön laadussa. Tämän takia on erittäin tärkeää pitää tehontuotto luotettavana, varsinkin saarekkeina toimivissa järjestelmissä.

Tämän työn tarkoituksena on tarkastella mahdollisuuksia rakentaa pienverkkoon hybridivoimalaitos, joka koostuu aurinkopaneeleista ja tuuliturbiineista yhdistettynä neste- tai kaasukäyttöisiin polttomoottoreihin. Työn rajoittaminen pienverkkoihin tuo esiin mahdolliset sijoituskohteet hybridivoimalaitokselle saarilla tai saarekejärjestelmissä, esimerkiksi kaivosalueilla. Myös hyvät sääolosuhteet saarilla, varsinkin päiväntasaajan alueella lisäävät kannattavuutta sijoittaa hybridivoimalaitokseen. Olemassa olevien voimalaitosten omaa kulutusta on myös tutkittu, ja lisäämällä aurinkokeräinjärjestelmä joka tuottaa kuumaa vettä moottoreiden sekä polttoainesäiliöiden esilämmitykseen, parantaa varsinkin aurinkoisilla alueilla sijaitsevien valmiustilassa olevien voimalaitosten hyötysuhdetta entisestään.

Nopeasti käynnistyvät ja hyvin kuorman muutoksiin reagoivat polttomoottorit sopivat erinomaisesti käytettäväksi uusiutuvien energiajärjestelmien kanssa, jolloin varastossa oleva polttoaine toimii energiavarastona, vastaten uusiutuvien aiheuttamien sähkön tuotannon vaihteluihin erittäin nopeasti.

Työn tärkeimmät tulokset tulevat ideaalisen hybridivoimalaitoksen simuloinneista. Aurinko- ja tuulivoiman sopiva suhde nestekäyttöisten polttomoottoreiden rinnalle ja moottoreiden tehontuotto tiettynä ajanhetkenä on esitetty. Myös hybridivoimalaitoksen uusiutuvien energiajärjestelmien sekä omaa kulutusta vähentävän aurinkokeräinjärjestelmän takaisinmaksuajat on laskettu. Tulokseksi saatu vajaan kuuden vuoden takaisinmaksuaika osoittaa että hybridivoimalat ovat erittäin kustannustehokkaita, varsinkin saarilla tai saarekkeina toimivissa järjestelmissä. Täten hybridivoimaloihin sijoittamista voidaan pitää suositeltavana.

AVAINSANAT: Hybridivoimalaitos, uusiutuva energia, saarekejärjestelmä

1 INTRODUCTION

Energy consumption in the world has grown year by year and is still increasing. Meanwhile, the human race has understood the importance of cutting down pollutions and therefore the utilization of renewable energy sources is improving in emission reduction. The power supply of renewable energy sources can though be lacking at some moments. Due to that, the Wärtsilä hybrid power generation concept includes combustion engines to improve the reliability and also an amount of renewable generation to cut down the emissions and increase the use of advantageous energy. Especially on islands the usage of renewable energy sources should be utilized not only because of good weather conditions, but also because of the increasing fuel costs and an expensive interconnection to mainland trough an electricity cable connection.

This thesis studies the profitability of Wärtsilä hybrid power generation concepts. Both solar and wind power are considered in a proper share with liquid or gas fuelled engines. The study not only shows an ideal share of renewable energy for reducing the emissions, but also the profitability in decreasing a part of the power plants own consumption by adding renewables that generate e.g. warm water for engine and fuel tank pre-heating for power plants in stand-by mode. The importance of Wärtsilä combustion engine is shown especially in the true flexibility. In power plants the engines can operate in base load, stand-by or peak load mode, as well as on back-up power basis.

For island energy operators, one of the main challenges is to switch to an environmentally sustainable energy production while ensuring a reliable, safe and economically viable production of electricity (EurElectric 2012). A perfect location for concepts like this is on islands, and due to the fact that most of the isolated small grid customers are from the sun-belt countries, the weather conditions and restricted grid size (less than 300 MW) support renewable power generation. Thus, the solar power has shown to be an efficient and suitable option, together with wind power. Therefore, the major emphasis in this thesis is made upon solar power, both concentrated solar power (CSP) mainly for engine preheating systems and photovoltaics (PV), as well as wind power.

The first chapter of this thesis deals with the Wärtsilä power plant. A general overview through the composition, different kinds of combustion engines, starting, operation, and finally some technical aspects are discussed. Chapter 3 presents challenges with power generation on islands as well as power quality issues. Chapter 4 gives a review of hybrid power plants' structure and different components. Also, wind and solar power generation and different storage systems are presented. The 5th chapter deals with the main subject, the hybrid power generation concept with Wärtsilä combustion engines. The optimal base-load power plant and the ideal amount of renewable energy are calculated, with the emphasis in keeping the costs in minimum and the grid reliable. Also, calculations of a possible energy storage system will be made. A review of power plants' own electricity consumption and minimization of it by utilising renewable energy sources is done as well. Chapter 6 presents calculations and concept examples for some ideal hybrid concepts. The payback times with different share of renewable penetration besides combustion engine power output at four different locations are calculated.

The aim of this thesis is to calculate and design the ideal share of renewable energy in a hybrid power plant combined with Wärtsilä combustion engines for off-grid or small grid (10–300 MW) solutions. The payback times for different set-ups and scenarios are calculated as well. Also, calculations for minimization of the power plant's own consumption with renewable energy and thus making it more efficient, are presented. This thesis is limited to small power plants (less than 100 MW) and does not consider the influence of subsidies, such as feed-in tariffs (FIT) or others.

2 WÄRTSILÄ POWER PLANTS

Wärtsilä power plants is a leading global supplier of highly efficient and modern power plants. With multi-engine and multi-fuel solutions and different load applications it can supply power on a range of 1 MW to over 500 MW, despite the location. Long-term operation and maintenance agreements are available for every customer. Effective, flexible and sustainable power systems are what Wärtsilä is producing nowadays.

The flexibility can be honoured due to the multiple operating modes, such as for example:

- Rapid load following at all times,
- Peaking during high demand periods,
- System balancing (fast frequency regulation), and
- Fast grid black start in case of power system black out.

Experience is highly valuated in the eyes of a customer. Wärtsilä has provided almost 49 GW of installed capacity in 169 countries until 2011. (Wärtsilä 2012a)

2.1 Composition of power plant

The Wärtsilä combustion engine power plant consists of several medium speed (500 - 1000 rpm) gas or liquid fuel engines installed in parallel. Wärtsilä also provides other power plants, e.g. for oil and gas industries, floating power plants and pumping applications.

Figure 1 shows a typical single line diagram with the voltage levels of a Wärtsilä power plant. The generating sets are coupled to the medium voltage switchgear, whose AC voltage level is 1 - 35 kV. The low voltage (400 V) switchgear is connected via a transformer to the medium voltage switchgear. If necessary there is also a high voltage switchgear for high voltage grid connections, coupled to the medium voltage bus bar via a transformer.

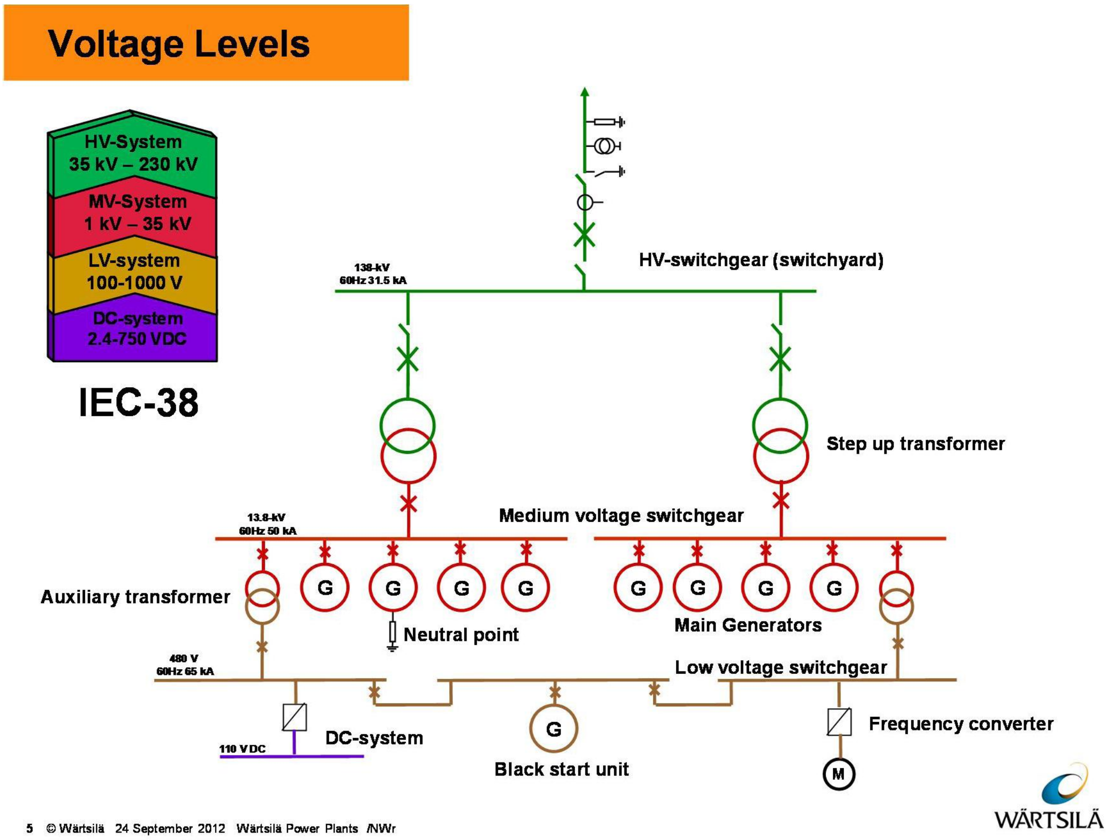

Figure 1. Wärtsilä power plant voltage levels. (Wägar 2012)

The maximum amount of generators coupled in parallel depends on the short circuit current of the switchgear. For example, this system with a voltage level of 13.8 kV and a frequency of 60 Hz, has a short circuit current of 50 kA. (Wägar 2012)

The automation system of the power plant can be divided into three main categories: control, protection and supervision. Controls for the power plant are:

- Engine fuel control (speed and active power),
- Generator excitation control (voltage and reactive power), and
- Process control.

Protection is supervising that the system is working properly. The breaker will trip and shut down the engine if the protection finds something abnormal. Supervision, on the other hand, gives operators information about the protection systems and the control status. Basically it supervises the whole plant status.

The operational flexibility can be described by the different automation functions. It supports reliably in all different kinds of operating modes. Thanks to the intelligent controllers, the solution provides an automatic, seamless transfer between the operating modes, e.g. true kW and power factor control, load sharing for both active and reactive power, for island mode operation and droop mode as backup. The automation in Wärtsilä power plants are based on the following blocks:

- WOIS, the operator's workstation for process displays, controls, alarms etc.,
- WISE, the workstation for logbooks and electronic documentation,
- PLC, the process control system of the plant equipment, and
- UNIC, the engine embedded control system of the engine and protection.

Remote control of the system and viewing the information from WOIS and WISE is also possible for the customer and technical support. All the functions have been developed and are continuously under development to be as easy and clear as possible for the user. (Wärtsilä 2012b)

2.2 Engine types

Wärtsilä's engine portfolio for power plants consists of medium speed, four-stroke engines. Wärtsilä's engines can be operated on a broad variety of fuels: heavy fuel oil, light fuel oil, crude oil, emulsified fuels, bio-oil, biodiesel, natural gas, and associated gas. In a power plant the power output range can be from 1 MW to over 500 MW, larger power plants consisting of more than 20 engines. The single engine power output lies between 1 MW and 23 MW. The model name of a Wärtsilä engine expresses the number of cylinders and the cylinder bore in centimetres and the letters for the type of fuel usage, i.e. a Wärtsilä 20V34SG is a 20 cylinder gas engine with a cylinder bore of 340 mm. Engines with the amount of cylinders from 6 to 9 have the cylinders arranged in-line, while engines with more than 9 cylinders are of the V-type.

Figure 2 illustrates different Wärtsilä combustion engine models. You may also find the possible power output range of power plants with the different types of engines. They are divided into three groups depending on the fuel type. Gas engines use gaseous fuel of different quality. Liquid fuel engines may use a variety of different fuels, such as Light fuel oil (LFO), Heavy fuel oil (HFO), Crude oil (CRO), Fuel-water emulsion (FWE) or Liquid bio fuel (LBF). The dual-fuel engines, however, as the name says, may be used with either gaseous or liquid fuel. They have two different injection systems and the fuel type can be changed automatically and instantaneously at any load. They can also be driven in fuel sharing mode, meaning simultaneously with both gaseous fuel and liquid fuel. (Wärtsilä 2012b)

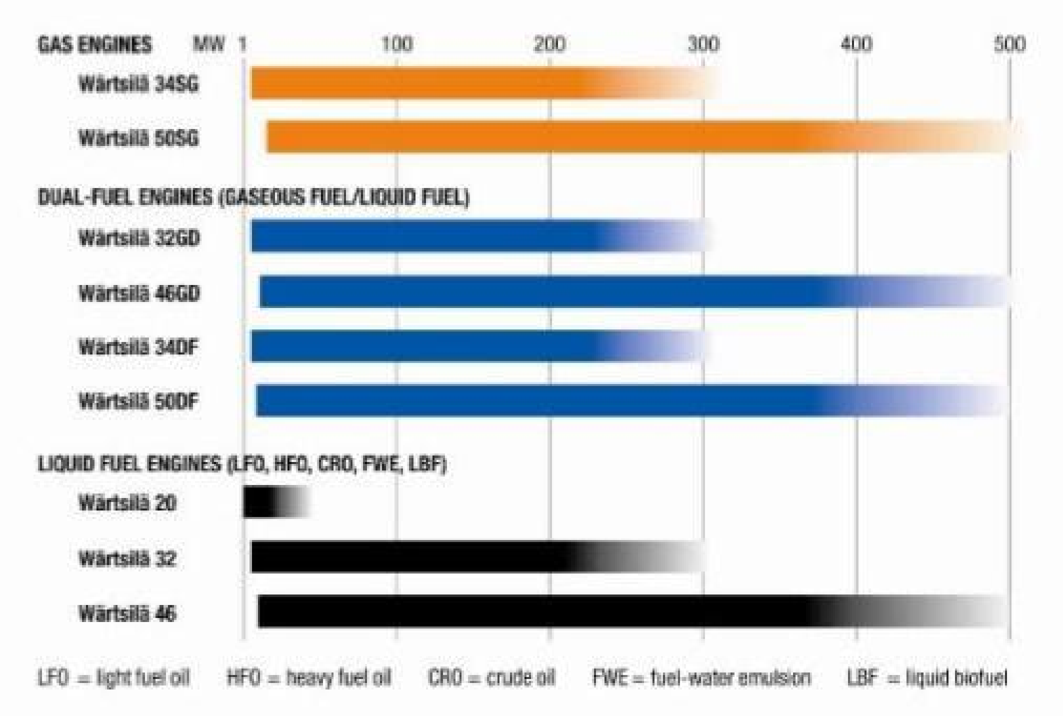

Figure 2. Output power range of the different Wärtsilä combustion engines in a power plant. (Wärtsilä 2012b)

2.2.1 Gas engines

The Wärtsilä SG engines are spark-ignited lean-burn otto cycle engines that run on gaseous fuel. The gaseous fuels can be divided according to quality. Liquefied natural gas (LNG) is the commercial pipeline gas. Other gaseous fuels are: biogas, associated gas and coal bed natural gas. These gases are not of as good quality as LNG. In SG engines the gas is mixed with air before the inlet valves. The gas-air mixture is then also fed into a small prechamber, besides the cylinder. The gas-air mixture in the prechamber is first ignited and the flames from its nozzle ignite the fuel in the cylinder. The efficiency in gas engines can be up to 48 %.

2.2.2 Liquid fuel engines

The liquid fuel engines run on many different fuel types as mentioned in Section 2.2. The most common are LFO and HFO. After the engine is started with air the fuel is injected to the cylinder at a high pressure by camshaft-operated pumps and the fuel is instantly ignited. The liquid fuel engines have been developed and are being developed all the time to be as efficient as possible. For example the “miller timing” reduces the work of compression and the temperature in the engine, which makes it more efficient and less polluting. (Wärtsilä 2012b)

2.3 Driving the engine

Before starting a Wärtsilä engine it should be preheated into 70 degrees in Celsius with hot water, if the fastest start-up time is desired. A preheated engine can be loaded according to the nominal loading performance, without straining the engine and hereby keeping its lifetime normal. The preheating of an engine requires a lot of power especially when several engines have to be preheated.

When starting the Wärtsilä engine, compressed air is injected directly into the cylinders. That will rotate the engine and start it. Also, a pneumatically driven starting motor can be used in some cases. The start-up times depend not only on the fuel type, but also on the engine size. After the pre-start-up procedures are done, the engine is rotated and accelerated to 5 % of the nominal speed. The fuel injection is activated after 5 seconds and the engine accelerates to its nominal speed. When the engine has reached its nominal speed, the generator is synchronized to the grid, and the loading of the engine can be started. When loading the engine, it has to be made gradually to keep the engine parts, especially the pistons without strain. Stepwise load application is also possible, but the load step has to be limited. Excessive load steps lead to a big drop in frequency. The maximum frequency drop allowed by the engine is 10 %, which however is unacceptable in most electricity grids.

The Wärtsilä combustion engine using gaseous fuel is able to drive a minimum load as low as 30 % of its maximum power output. The liquid fuelled combustion engine, however, is able to drive a minimum load of 10 % of its maximum power output, although only 60 - 70 % of the time. Another thing worth mentioning is that the Wärtsilä engine power plants usually consist of several engine sets, which mean that depending on the load, only the optimal amount of engines are generating power. (Nyman 2008: 17 - 18)

Figure 3 shows the differences in the efficiency of one or several Wärtsilä combustion engines using gaseous fuel and a gas turbine depending on the power plant total power output. It is also worth notifying from the figure that the total efficiency increases with several generating sets compared to just one.

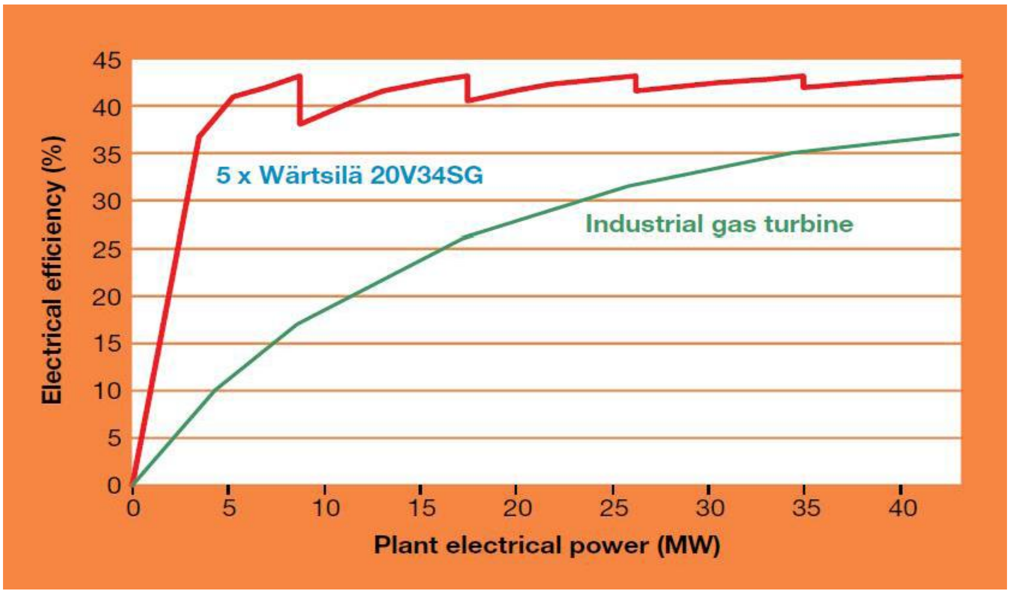

Figure 3. Electrical efficiency for combustion engines and a gas turbine. (Wägar, Östman,Wideskog, Linde 2012)

2.4 Advantages of combustion engines

The aspects of combustion engines often cited are that they are polluting, of old technology, slow etc. But actually according to researches it has been found out that a combustion engine has good flexibility, high efficiency and when connected to the grid, makes the power production more reliable. It also has a very fast start-up as well as stop and relatively low equipment costs.

Beneath some of the benefits of both gas and liquid fuel engines are listed:

- Excellent plant availability and reduced need for backup capacity due to multi-unit installation,
- High part-load efficiency,
- Net plant electrical efficiency of 44 - 48 %,
- Fast start-up, 5 minutes from hot standby to full plant load, and
- Maintenance schedule independent of the number of starts or stops. (Wärtsilä 2012b)

The particularity of the engine is shown in Figure 4 by values and features which are divided into five different phases. The first phase is the fast start-up of the engine. It provides the grid with power in less than one minute, which improves the grid stability. The second phase shows the great efficiency and life cost of the engine when providing base-load. The third phase is about fast load following, which is crucial when balancing renewable generation. Part four shows that the engines can be driven even when the load is low. That reduces the fuel costs and emissions. The fifth phase shows that the engines can be shut down ultra-fast if there is no need for power generation at that moment. (Wägar et al. 2012)

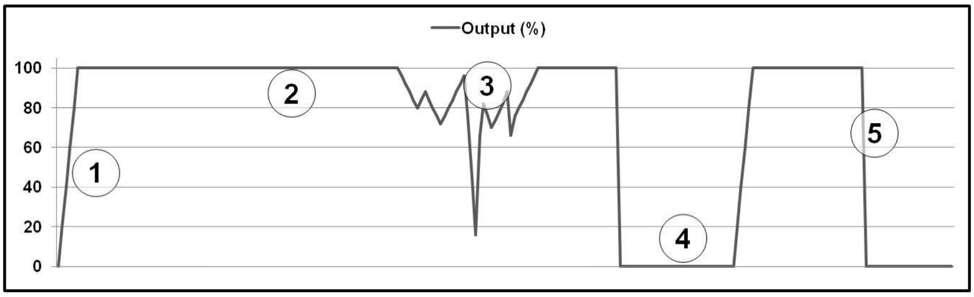

Figure 4. Engine output particularity. (Wägar et al. 2012)

2.4.1 Fast start-up

As mentioned earlier in Section 2.3, the combustion engine has an extremely fast start-up. In Figure 5 it is seen that the stand-by preheated (70° C) engine will start within only 30 seconds, during which pre-lubrication is done, and reach full speed in 60 seconds. At the 60 second -mark the engine will synchronise with the grid and start to take load. The engine will reach its full load in 5 minutes and can be shut down in 60 seconds.

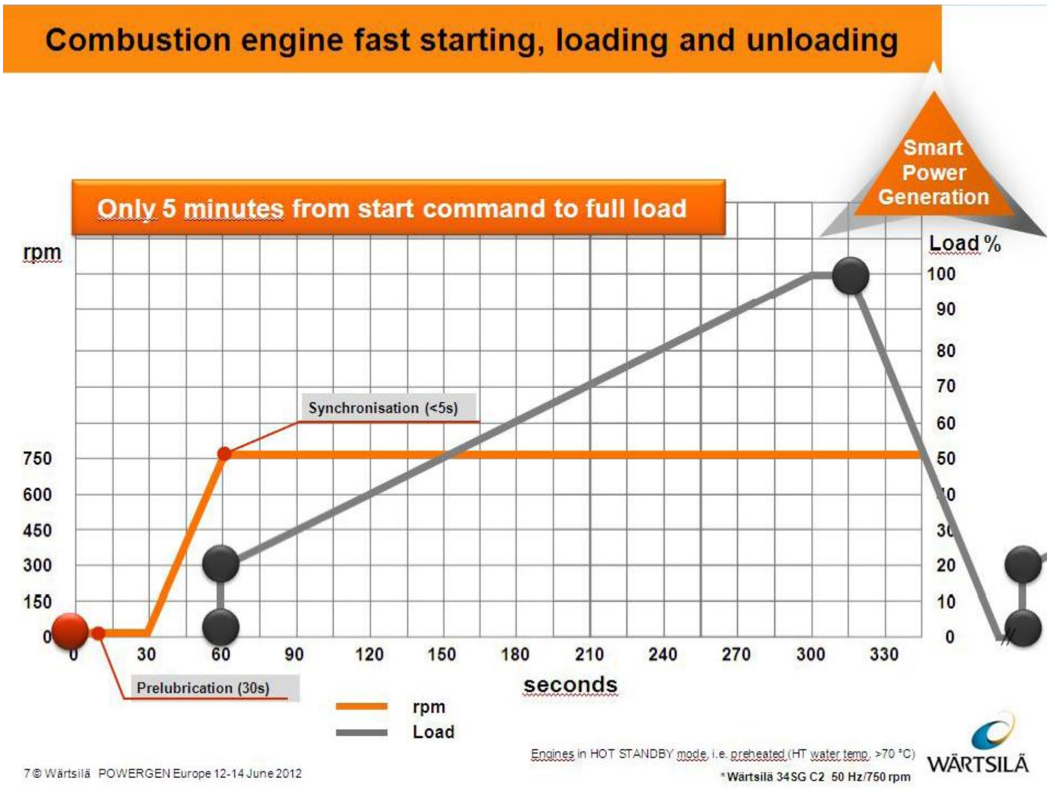

Figure 5. Start-up, loading and unloading time of a Wärtsilä combustion engine. (Wägar et al. 2012)

2.4.2 Inertia and its contribution to the system

When speaking of inertia and its contribution to the power demand in the grid, it is mentioned as an important part of keeping the frequency on an allowed level. The stored energy, in the rotational mass of large spinning machines, gets released to the grid when a disturbance occurs or power is needed. (Leslie Bryans & Alan Kennedy 2007)

The inertia constant, H, can be given by the formula

$$H = \frac{J\omega_m^2}{2P}, \tag{1}$$

where J and ω_m represents the engine's inertia and angular speed, and P is the power of the engine. (Ackermann 2005)

Comparing to a gas turbine, the inertia is relatively low for a combustion engine. According to a study, increasing the share of combustion engines does reduce the inertia, which could lead to a faster frequency drop. However, because of the speed of the engines under study, this is compensated by the speed of primary response of these engines. It is considered as an extreme advantage of the combustion engines, since the frequency droop coverage and the fast reaction to the power demand are key parts of grid stability. Figure 6 presents a simulated situation of a frequency drop and the coverage with different share of combustion engines in a high wind power system. You may see that the frequency recovery is faster with a larger share of engines, and it also does not fall as low as in a system with a smaller share of engines. (KEMA 2012: 34)

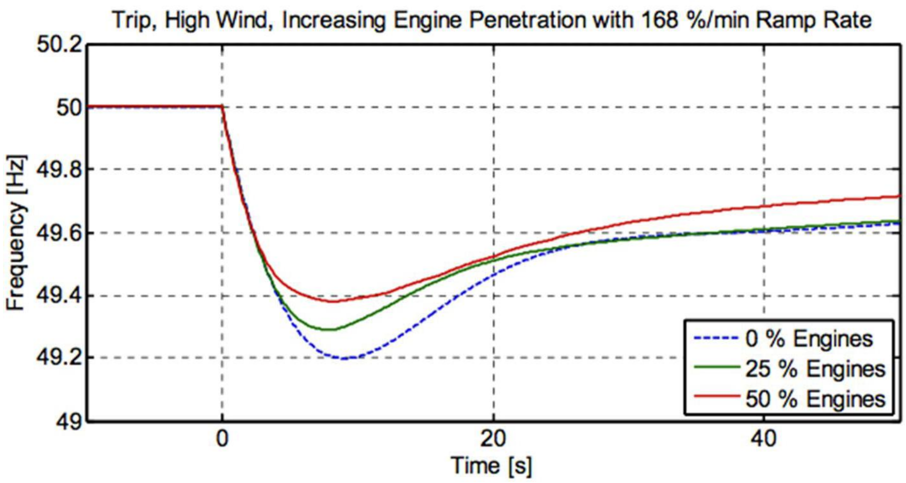

Figure 6. The frequency drops in a system with different share of engines and high wind penetration during a trip. (KEMA 2012: 26)

2.5 Modularization

When constructing a Wärtsilä power plant nowadays, it is much easier than decades ago, since it is made of prefabricated modules which are mounted together at the power plant site. The module portfolio consists of several module types for every option. Rapid installation time is one of the main advantages of modularization, which means a reduction in overall cost of the assembly for the customer. Prefabrication also ensures high quality products, easier shipping in containers and a more accurate price at sales stage. The modules are most often installed around the engines, inside the power house. However, modules can be installed outside also, e.g. at fuel process. Figure 7 illustrates the gas engine modularization blocks with mounted generating sets. The easiness of mounting these modules can be noticed of the organised setup, instead of building everything from scratch at the site. (Wärtsilä 2012b)

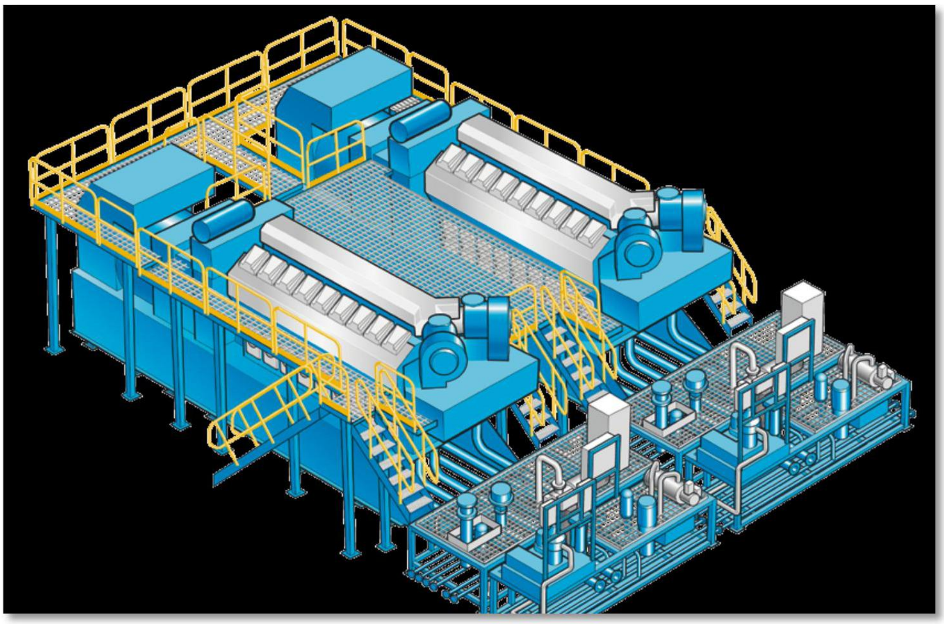

Figure 7. Wärtsilä modularisation blocks with full generating sets mounted. (Wärtsilä 2012b)

3 CHALLENGES WITH POWER GENERATION ON ISLANDS

The electricity demand in the world is increasing and meanwhile pollution should be decreased. On islands the biggest challenge is definitely the transportation of fuel and also the small land area available for big storage tanks. Therefore, utilizing local renewable energy sources in a larger extent would be a great leap forward in solving the problems. The sun is radiating energy to the surface of the earth every day. Windy days also create an opportunity to harvest energy for usage. Besides, power plants based on renewables are practically free of pollution during the operation time. The islands reviewed in this Chapter are mainly located in Europe.

3.1 Power on islands

Emission reduction on islands is a challenge, because islands often produce most of the power with liquid fossil fuels. The Industrial Emissions Directive's (IED) requirements of reducing emissions will make it difficult and costly for the islands. The challenge is to make the energy production less polluting, while keeping the grids safe and reliable. The target for RES 2020 is set to reduce 20 % of the greenhouse gases meanwhile adding 20 % renewable energy. Installing renewable energy sources on islands is more challenging than on mainland grids. Some of the challenges are:

- Relative plant size (a 3 MW power plant produces 3 % in a 100 MW grid),
- Sufficient back-up power needed,
- Storage, and
- Frequency and voltage regulation.

Due to increasing energy consumption, increasing fuel price, long distances and required space for fuel storage, the renewable energy production has become a good choice for islands. By combining with flexible generation, smart grids and switching old oil power plants to newer and more efficient ones or to gas power plants, the requirements can be achieved. In Figure 8 the power demand outlook on EU islands is shown.

As can be seen, a rapid increase in the power demand at least for the next seven years is forecasted. (Eurelectric 2012: 17, 21)

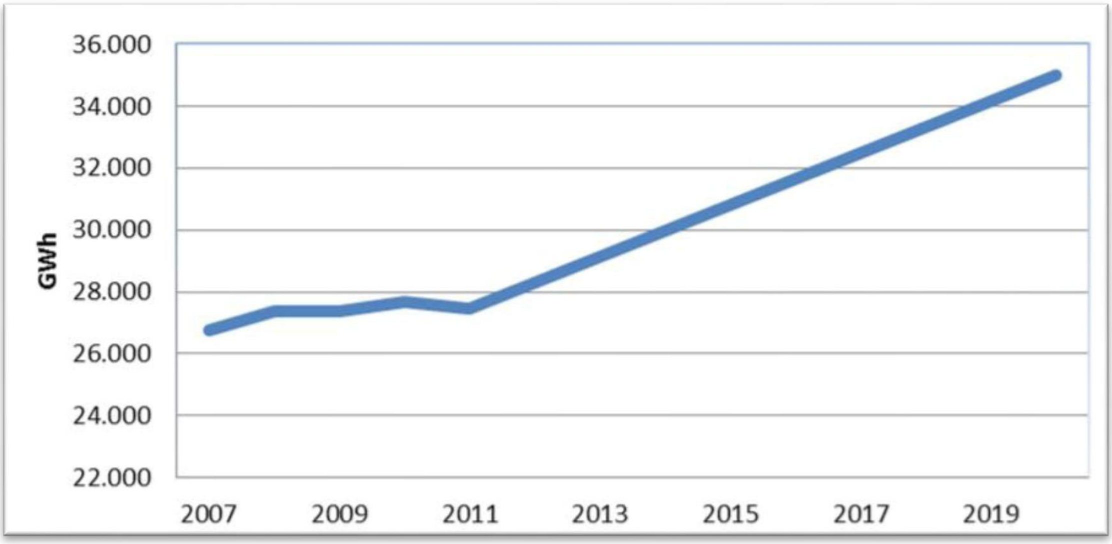

Figure 8. Power demand outlook on EU islands in past, present and future. (Eurelectric 2012: 13)

An interconnection between the mainland grid and the island has also been discussed as an alternative. It would increase the security of power supply, import low pollution energy and reduce the energy cost due to a larger grid market. The interconnection could be a high voltage AC or DC subsea cable. But the investment costs, especially due to long distances, make it a less advantageous alternative. In addition, one cable doesn't make the system reliable, since if it breaks, the island becomes powerless. Also, repair costs and insurances for the subsea cable are very expensive. In year 2013 operational 120 km long high voltage alternative current (HVAC) interconnection between Malta and Sicily is estimated to cost 200 M€, which makes the price around 1.7 M€/km. (EurElectric 2012: 19 - 26)

3.2 Switching from oil to gas

Since oil-fuelled engines are considered highly polluting, another fuel option for combustion engine power plants is liquefied natural gas (LNG). LNG consists mostly of methane that has been liquefied by cooling it down to -163 degrees in Celsius. Since methane has the lowest carbon ratio (75 % of weight) of all fossil fuels, it is considered as a good replacement for oil. The carbon ratio for heavy fuel is around 87 % of its weight. When natural gas is liquefied it takes only 1/600 of space compared to it in gaseous form. The space-saving method simplifies transportation a lot and therefore makes it an even better fuel for power generation. When allowing it to warm, it evaporates and returns into gaseous form. A major problem with switching oil power plants to natural gas on small islands is the space required for storage tanks and also the difficulties in transportation of small amounts. Moreover, the high cost of LNG re-liquefaction facilities, has made it inefficient to build them due to the small power generation. Therefore, other options are seemed as better choices for small power demand on islands, e.g. renewable energy. Even though the overall role of oil is decreasing, several islands are still planning or constructing new diesel-fuelled generation units to either increase overall generation capacity or to replace ageing plants with more fuel-efficient and less polluting engines. Also, diesel is considered by many as an important back-up fuel for balancing renewable energy generation. (EurElectric 2012: 19 - 26)

3.3 Power quality

The power quality is to be considered affected when connecting renewable energy sources to the grid. The grid-connected systems have to provide so-called ancillary services like stabilising the grid voltage, providing reactive power, active filtering of harmonics or fault ride-through in case of voltage dips. All of the inverters must be able to provide reactive power if the grid voltage needs stabilization. The five major issues according to Mohod & Aware (2006) are:

- Voltage fluctuation on grid,
- Switching operation of wind turbine on grid,
- Voltage dips on grid,
- Reactive power, and
- Harmonics.

Injection of wind power in the grid affects the voltage quality. In the IEC61400-21 the power quality of wind is defined as: active and reactive power capabilities and control, response to voltage dips and emission of voltage and flicker. Operation of the start-up at cut-in wind speed and rated wind speed may cause significant voltage variations. The wind turbines with frequency converters can either supply or consume reactive power according to needs. (Ackermann 2005: 160 - 165)

3.3.1 Voltage issues

Voltage issues, such as voltage fluctuations and flicker can be caused by wind turbines, but normally it is changes in the load that induce the voltage fluctuations. Another problem is the voltage dips. They are defined as a temporary reduction of the voltage to a value less than 90 % of the nominal voltage, followed by a voltage recovery after 10 ms to 1 min.

The total harmonic distortion (THD) should be according to EN50160 less than 8 % of the voltage. Thyristor-based converters often emit harmonic currents that may influence the harmonic voltages. However, such converters are not used much in wind turbines these days. (Ackermann 2005: 91 - 93)

3.3.2 Frequency variations

The frequency variations occur when there is an imbalance between the production and consumption. If there is a sudden disturbance in the balance, such as loss of a generation set or a large load change, fast activated reserves have to take part in the frequency control. The frequency control is usually managed by conventional power plants, but in off-grid solutions, these distributed generation power plants have to take care of it. The frequency control is divided into three phases. In the first phase the rotating masses, inertia, will contribute rapidly to the frequency deviation. If the deviation exceeds, controllers will be activated. In this second phase, so called primary frequency control, the power input has to be changed to obtain the frequency at a demanded level. When the power balance is restored, the frequency will be returned to its nominal value. That is the third phase, even known as secondary frequency control. (Ackermann 2005: 146)

A large number of distributed generation (DG) units in the grid will make frequency control more difficult. To avoid large frequency deviations, DG units will have to contribute to frequency control. In order to contribute to the frequency control, the DG units should be able to increase their power output when needed. (Morren, de Haan & Ferreira 2005)

The mechanical energy in variable-speed wind turbines is not released when the grid frequency drops, because they are decoupled by power electronic converters. Therefore, the energy stored in the rotating mass will not be released when the frequency in the grid drops. In practice, it is much more likely that the frequency decreases than increases. (Ackermann 2005: 907)

3.3.3 Reactive power

PV generators and some types of wind generators use power converters. The reactive capability of converters differ from those of synchronous machines because they are normally not power-limited, as synchronous machines are, but limited by internal voltage, temperature, and current constraints. Unlike double-fed or full-converter wind turbine generators, induction-based wind generators without converters are unable to properly control reactive power. When talking about renewable energy systems and reactive power issues, there is no actual issue, meaning that renewable energy systems are good ancillary for providing or consuming reactive power. It is though economically to provide the reactive power in the grid with external static and dynamic devices such as static VAR compensator (SVC) and STATCOM devices.

Large wind or solar power installations can have negative effects regarding power quality, especially when they constitute a high percentage of total power produced, but even when the penetration levels are around 10 %. The most commonly reported problem associated with high PV penetration on distribution feeders is steady-state voltage problems. The steady-state voltage problems are situations when the voltage level is much higher or lower than the nominal voltage, typically over 10 %. Severity depends on the feeder characteristics and location of the PV generation along the feeder. The impact is typically reduced as the distance to the renewable power source shortens. There are couple hardware solutions for diminishing the impact. They can broadly be divided into two groups: reactive power control and energy storage.

Nowadays utilities use reactive power control primarily for power factor correction. But this technology also plays an important role in controlling voltage levels. Volt ampere reactive (VAR) devices inject energy to smooth the swings in supply and thus keep the voltage at an acceptable level. The inverters that connect PV systems to the grid can function as controllers, because they can consume or provide reactive power quickly. Also, battery energy storage systems can be used to provide voltage smoothing, when equipped with the right controls. Battery charging is not sensitive to voltage intermittency and once the batteries are charged, they provide a good and fast power source. Battery storage can be located at the substation or distributed along the feeder. An additional benefit is that it can instantaneously provide power to minimize service interruptions. (Abi-Samra 2012)

It should be noted that that both PV plants and converter-based wind power plants are technically capable of providing reactive capability at full output. The difference is that this kind of requirement is new to the solar industry compared to the wind industry. (Ellis, Nelson, Von Engeln, Walling, McDowell, Casey, Seymour, Peter, Barker and Kirby 2012)

3.3.4 Grid codes for wind and solar power

Interconnection standards for wind power generation, known as “grid codes” are relatively mature in Europe compared to standards in North America. Standards vary across transmission operators, but there are intensions in standardising them. Power factor design requirements are expressed as a Q vs. P capability curve. These charts specify reactive power requirements across the full operating range of active power, not only at full output. The power factor design requirements at full output vary between unity and 0.9 under or overexcited at the point of connection. Most grid codes recognize that reactive power capability depends on voltage conditions and include specifications to that impact.

Interconnection requirements for solar PV systems installed at medium voltage (10 kV to 100 kV) were recently put into effect in Germany. The power factor design criterion is +/-0.95 at full output, which requires inverters to be oversized or de-rated. This standard also requires dynamic reactive power support during voltage excursions. (Ellis et al. 2012)

4 HYBRID POWER PLANTS

As mentioned earlier the utilization of non-polluting energy from the sun and wind is nowadays of high interest. The so called hybrid generation concepts consist of two or more power generation systems utilizing different energy sources. Often it is solar power or wind power combined with a secondary generation system. It is extremely important to ensure the power supply in an off-grid power generation system. Because of the unpredictability of the weather conditions, the renewable generation systems alone are halting. Due to this, combustion engines, gas turbines or fuel cells as a secondary generation, besides solar or wind power will ensure the continuous power delivery. (Hyytinen 2012)

Unfortunately, negative aspects of renewable energy, due to its high cost, withdraw governments' barriers and lack of subsidies that eventually brake down the development of renewable energy technology. However, increased fuel costs and the approach of saving the environment will hopefully increase the use of renewable energy sources in the near future. (Bloomberg, Heidell, Bernstein, Sugandha, Tuladhar and King 2013)

4.1 Wind power

Wind energy has been utilized for a long time. Nowadays wind energy systems are increasing rapidly all over the world. The fast development of wind technology has made it profitable, but in the meantime also complex. One has to understand the aerodynamics and the newest techniques to develop it to an even more efficient non-polluting energy production. The largest wind turbines generate power up to 8 MW, but somewhat smaller ones are more common.

There are a couple different kinds of wind turbines. In early 1990's the standard installations were fixed-speed turbines. Within the past years, the variable-speed turbines have become the dominant type among the installed wind turbines. The advantages of the variable-speed wind turbines are improved power quality, increased energy capture and reduced mechanical stress. There are some disadvantages though, such as, losses in power electronics and the increased equipment cost due to more complex structures. (Ackermann 2005)

In Figure 9 the structure of a horizontal-axis wind turbine is shown. The different parts in a wind turbine are numbered and listed, starting from the blades, ending to the tower. Beside of these there are a lot of other parts mounted up in the wind turbine, such as converter and brakes.

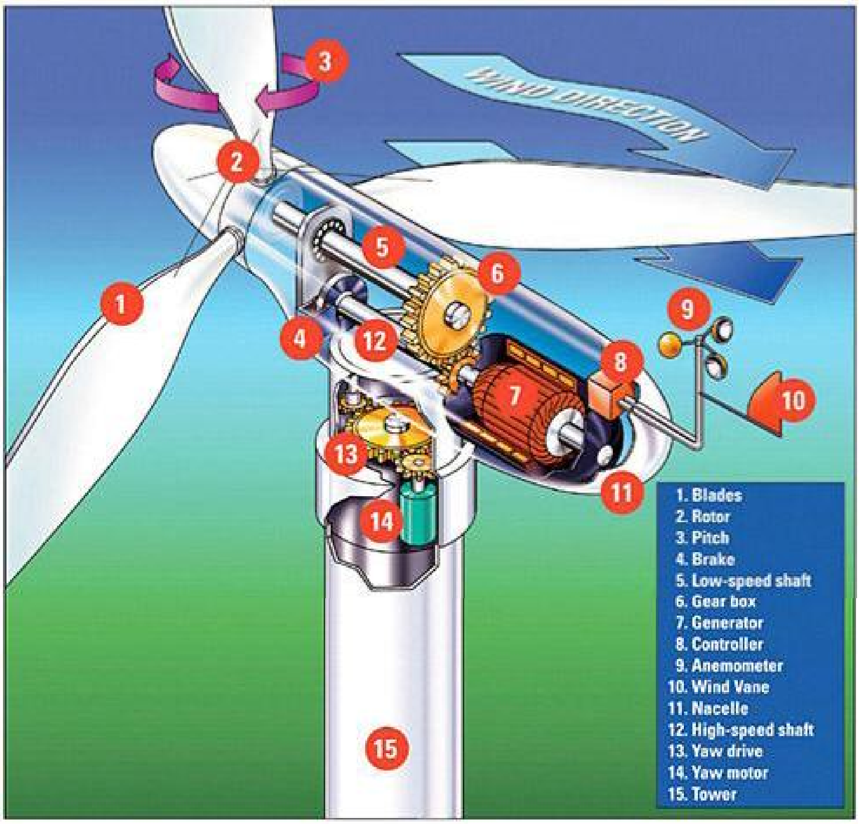

Figure 9. A wind turbine structure, with all the different components listed. (Alternative Energy News 2012)

4.1.1 Different wind power turbines

Wind turbines can be classified into two different categories depending on their axis orientation. The axis can be either vertically or horizontally oriented. The more popular turbine is the horizontal-axis wind turbine, which typically has three blades. There are four different types of wind turbine generator technologies (WTG):

- Fixed speed WTG,
- Limited variable-speed WTG,
- Variable-speed WTG with double fed induction generator (DFIG), and
- Variable-speed WTG with front-end converter system.

The variable speed WTGs are more common for bigger turbines nowadays, due to the fact that they are aerodynamically more efficient and have lower mechanical stress and lower voltage fluctuations. The variable speed WTG with permanent magnet synchronous generator (PMSG) and front-end converter system can be seen as the most efficient WTG nowadays, since it is smaller and lighter than the one with a DFIG and it also does not require slip-rings. Another benefit is the fact that it does not need a gearbox.

If a large amount of wind power is installed within small perimeter, the wind variability can have a significant impact on the voltage profiles. The variable-speed WTGs do not provide the system with inertia, since there is a converter installed between the wind turbine and the grid. That can lead to frequency instabilities. The DFIG's may also "crow-bar" during a fault and can consume large amounts of reactive power, which can disrupt the stability of the grid. (Kundur 2012)

4.1.2 Wind power production

The energy in the wind is actually created by the temperature changes on the surface made by the sun. An ideal equation for the power of wind is

$$P = \frac{1}{2}\rho A V^3, \qquad (2)$$

where ρ is the air density, A is the area the air mass flows through and V is the wind speed.

As can be calculated from the wind power formula, an increase of 10 % in wind speed will result in a 30 % increase in the available power. However, according to disc theory the maximum power that can be obtained from the wind without any power losses from harnessing the wind is 59 %. This is the so called Betz limit, which was discovered by Betz in 1926.

Wind turbines have so called cut-in and cut-out speeds. The cut-in speed is the wind speed at which the turbine starts rotating and thus generating power. Normally the cut-in speed is around 4 m/s. The cut-off speed is the wind speed at which the turbine stops rotating. The cut-off speed is a precaution measure for protecting the wind turbine, e.g. during a storm. The cut-off speed is typically around 25 m/s. In figure 10 the power curve for a 2 MW wind turbine is shown. Besides the cut-in and cut-off speeds shown in the figure below, one may see the average and rated wind speeds and their different power outputs. (Ackermann 2005: 33 - 36)

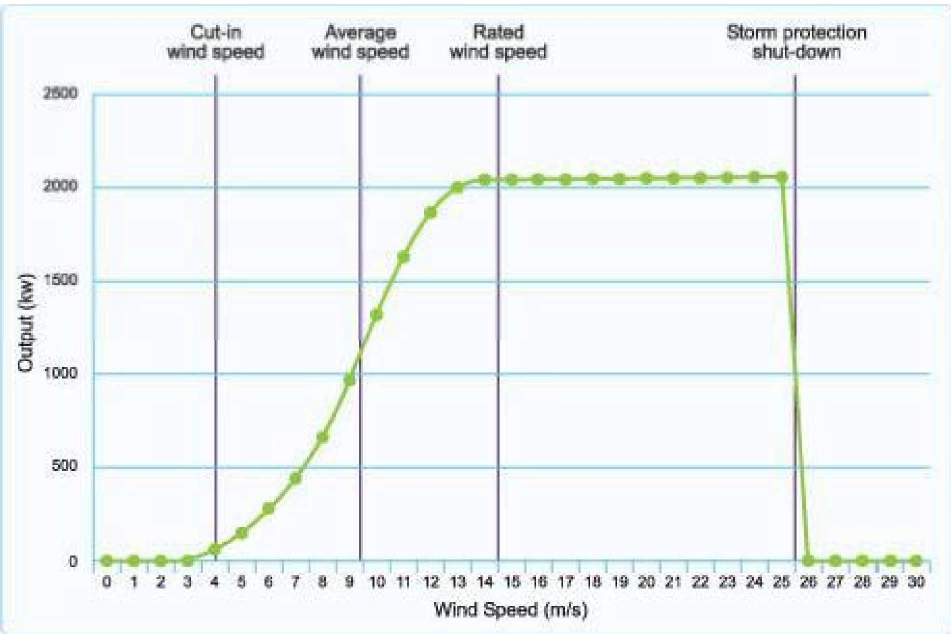

Figure 10. Wind power curve in changing wind speed. (Partnership for renewables 2010)

When choosing the size of the wind turbine, bigger wind turbines are more efficient, but bigger is not always better. The local lifting equipment might not have enough height for building big wind turbines, since only the diameter of a 5 MW wind turbine is over 100 m and adding the hub height of approximately 90 m gives a total height of 140 m. Therefore, installing a larger amount of smaller wind turbines would produce the same amount of power and also harvest the wind power on a larger area. However, smaller wind turbines have a smaller inertia, which affects the power smoothing negatively. (Cardenas, Pena, Perez, Clare, Asher & Vargas 2006: 1132)

4.2 Solar power

The sun radiates 174 PW energy to the earth, of which approximately 70 % hits the ground. The increasing research and development of solar power makes it an attractive choice of energy source nowadays. The radiation is at its highest during the noon, when also the electricity consumption is peaking, i.e. due to air condition in sunny areas. Therefore, the usage of solar power is suitable for loads of many consumers. (Klimstra & Hotakainen 2012) In Figure 11 is the yearly solar irradiance in the world presented. One can notice the high irradiance in sun-belt countries, near the equator. In the particular area, there are lots of islands and thus possible customers for hybrid solar power systems.

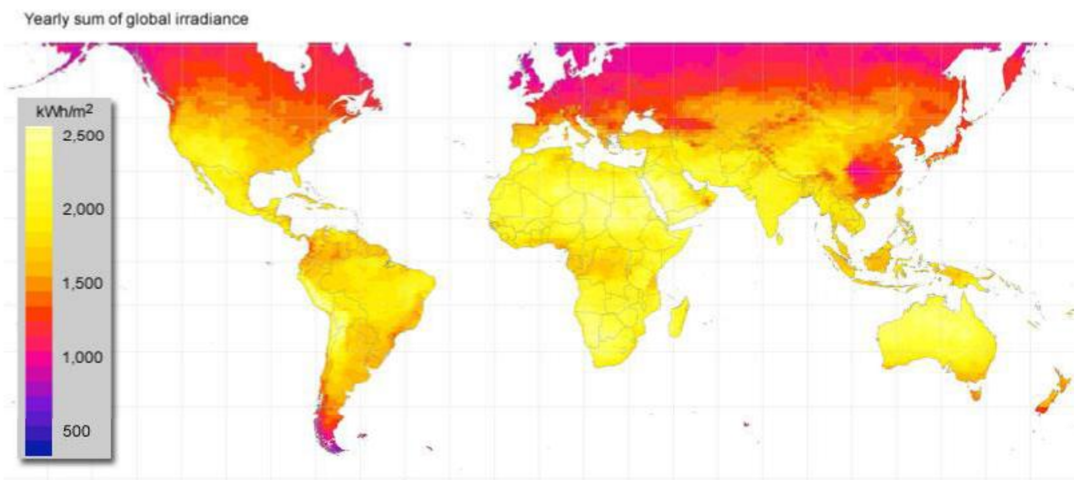

Figure 11. The yearly solar irradiation map of the world. (Green Rhino Energy 2012)

In grid-connected solar power systems the feed-in tariffs are the most cost effective policy instrument. The payback time of grid-connected PV systems decreases from decades to just a couple few years with the help of FITs. Nevertheless, in stand-alone systems the use of solar energy is already worthwhile, especially in the sun-belt countries. (European Photovoltaic Industry Association 2012)

4.2.1 Photovoltaics

The photovoltaic panels consist of several solar cells, which absorb the energy of the photons of the sunlight. The energy of the photons will create an electric field between the front and the back contact. The front and back contacts are constructed of a semiconductor. The most common semiconductor for PV cells is silicon (Si). In Figure 12 is the structure of a solar panel presented. (Hyytinen 2012)

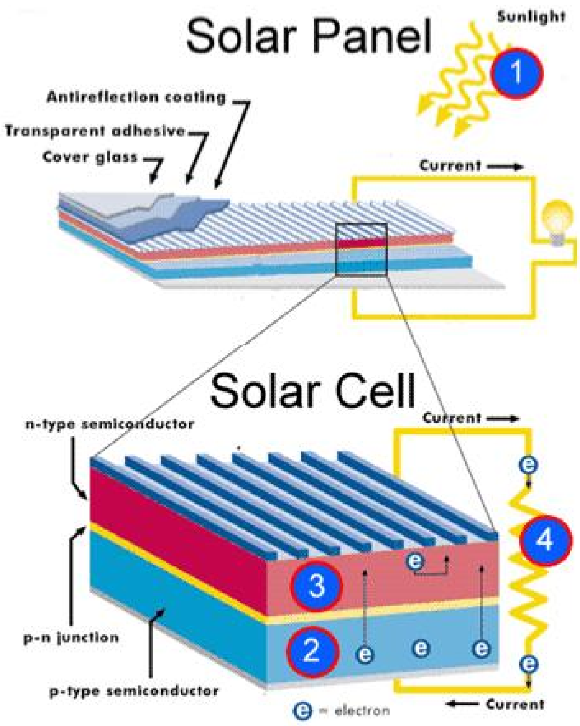

Figure 12. The structure of a solar panel and a solar cell. (Solar Cell 2012)

Load current in a PV cell is

$$I = I_L - I_0 \left(e^{\left(\frac{U+IR_S}{\alpha}\right)} - 1 \right), \tag{3}$$

where I_L is the light current of the PV cell (in amperes), I_0 is the saturation current, I is the current of the load, U is the PV output voltage (in volts), R_S is the series resistance of the PV cell (in ohms), and α is the thermal voltage timing completion factor of the cell (in volts). (Hyytinen 2012)

Due to significant improvements in technology, cheaper raw materials, highly competitive market and manufacturing scale, the price of photovoltaic panels has decreased to an affordable level. As can be seen in Figure 13 the price of photovoltaic panels has decreased steadily for the past 7 years, meanwhile the price of crude oil has raised significantly. According to this the use of PV panels is nowadays an even more interesting choice for new power generation systems. (Solar Frontier K.K. 2012)

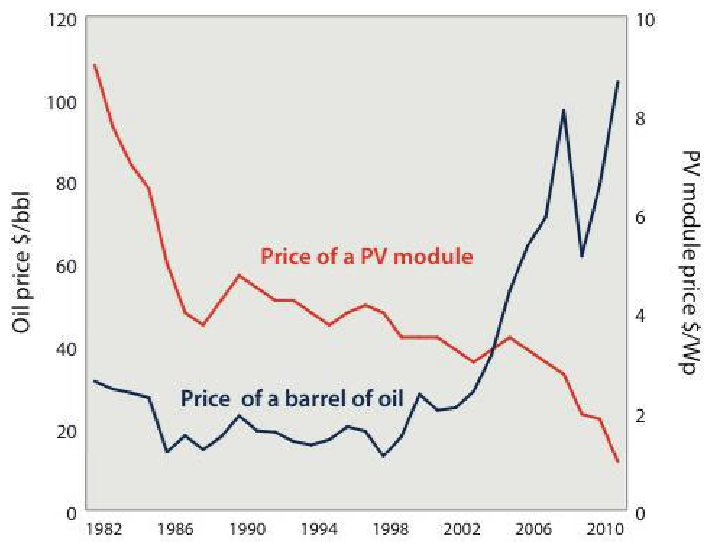

Figure 13. Oil and PV module price change for the past 30 years. (Solar Frontier K.K. 2012)

4.2.2 Concentrating solar power

Concentrating solar power (CSP) is also a good way of using the energy of the sun rays. As the name describes, it harvests energy by concentrating the sun rays to one point and thus heating up a fluid to a high temperature, which in turn warms up water that drives a steam turbine to generate electricity. There are three different CSP solutions, trough systems, power tower systems and dish or engine systems. We will concentrate on the parabolic trough system, because of its easy installation and efficiency in small systems.

The trough system consists of U-shaped parabolic mirrors in a row, called concentrators, which are tilted towards the sun. As seen in Figure 14a, in the middle of the concentrator is a pipeline, called the receiver, which goes through the system. Due to the shape and surface of the parabolic concentrator, sunlight heats the fluid running in the pipeline up to 400 degrees in Celsius. The sunlight hitting the receiver is 70 - 80 times more intense than ordinary sunlight due to the shape of the concentrator. (Solar Energy Programmatic Development EIS)

(a) (b)

Figure 14. A schematic diagram of parabolic trough system (a). A parabolic trough system in rows (b). (Solar Energy Programmatic Development EIS 2012; Nepsolar 2012)

4.3 Structure of hybrid power plant

The structure of a hybrid power plant varies, depending on the combustion engines, and the other power generating units. In Figure 15 a typical hybrid power plant with wind turbines, PV's and diesel engines is shown. It is also backed-up with a storage system. The challenge in designing the system lies besides the proper amount of power generation for the load, also in the function inside of the power plant, i.e. decisions whether constructing the majority of system with an AC or a DC bus, and also the optimal controlling between the power generation units has to be in order.

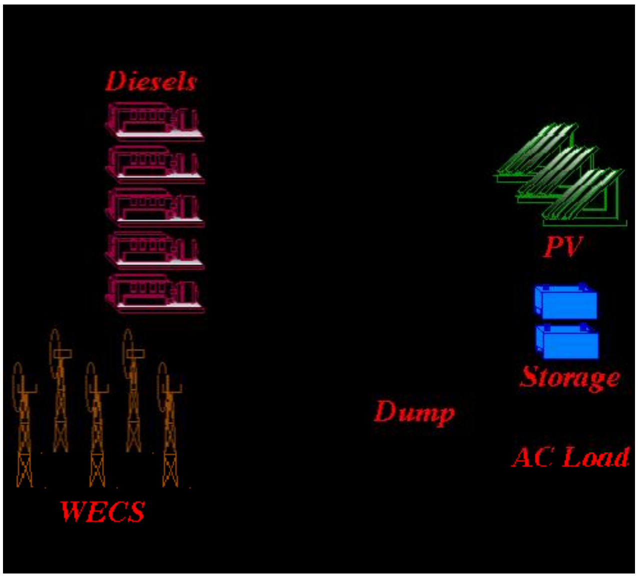

Figure 15. Hybrid power plant structure with PV, wind turbines, diesel engines and storage. (Wind energy (Beijing) co LTD 2010)

4.4 Electrical components for hybrid power plant

Besides the power generating units, there are a lot of components in a hybrid power plant. The most significant is the inverter, representing 5 to 25 % of the total cost of a PV system. Other components are cables, fuses and automation and telecommunication components.

4.4.1 Inverters

The inverters are the second most significant part in a PV system. The PV panels are the most important and most expensive as well. Inverters represent 5 - 10 % of the whole PV system cost in a commercial scale on-grid system and 15 - 25 % of a residential off-grid system. The function of the inverter is to convert DC power to AC power through the use of power electronics circuitry. The transistor based bridge in the inverter is usually made of semiconductor switches, such as mosfets or insulated-gate bipolar transistors (IGBT). They are operated in either a conducting or blocking state, which is switched on and off at high switching frequency (2 - 20 kHz). The result with a help of a filter will be sinusoidal AC at the frequency of 50 or 60 Hz. The controller is one of the key components in an inverter. It implements the algorithms that control the power semiconductors and also provides maximum power point tracking. The maximum power point tracker is reviewed more deeply in Section 4.4.3. The inverter has switches on both DC and AC side for disconnecting it safely from the grid. The inverters have also over-current protection devices on both sides. These are often shown as fuses but might also be accomplished with circuit breakers.

For grid-tied systems the inverters have to regulate the AC power that flows into the grid and meet the requirements of different grid standards, depending on the country. Off-grid inverters on the other hand have a slightly different function. They have to regulate the AC voltage that is supplied to the local load, which needs a fast dynamic response to keep the system reliable in operation, since the voltage might fluctuate from - 30 % to + 25 % of the nominal voltage. The inverter also needs to be capable of providing a quick motor inrush current which requires lots of power for a short period of time, meanwhile being efficient at marginal power levels. The off-grid inverter is often integrated with a charge controller, whose function is to control the power flowing to and from a storage system. The inverter must also comply with electric safety codes and also regulations regarding electromagnetic compatibility (EMC). The most important characteristic of the PV inverter is its efficiency. It is normally inefficient at low power levels, increases and reaches a peak in the middle of the power range, and then drops at higher power levels. The efficiency also varies at different DC voltage levels.

Another important characteristic is the ratings of the inverters enclosure. There are different ratings, depending on where the inverter is installed. For inverters installed outdoors, there are some enclosure ratings, such as NEMA 3R/4 or IP65.

When choosing proper-sized inverters to a system the power rating of the inverter should not be lower than the possible power obtained from the PV array, or the inverter will “clip” the power and supply will be lost. It is normal though that PV nameplate DC will not be reached and therefore a factor 1.2 is used when sizing the inverter, meaning if the PV nameplate DC power is 12 kW a 10 kW AC power inverter is sufficient. (Luque & Hegedus 2011: 855 - 859, 969 - 974)

4.4.2 AC, DC or AC/DC bus

When choosing between AC and DC bus, there are several things that have to be considered, such as the distances between the generating units and the power plant, the investment cost, load type and size, the voltage levels etc. According to (Gabler & Wiemken 1998) the AC bus configuration is comparable in performance to a conventional AC/DC bus system. Here it is shown that if maximum power point tracking is included in both systems, the AC bus system requires about 10 to 18 % more electricity from the engine-driven generator. In contrast, the DC bus system requires at most 2 to 3 % more electricity from the engine-driven generator.

The impedance of the cables has a bigger influence in power losses when operating with alternative current in comparison with direct current. This is due to the reactance, which does not have effect on the direct current. Using direct current makes it also possible to locate the generating system further from the power station, because the voltage drop is lower than for alternative current. Furthermore, the strain of the components is bigger when using alternative current, because of its pulsating waveform. (Hiekka 2012)

The major challenge in designing the DC distribution is the choosing of the components, such as switches, bus bars and enclosures for different currents. The peak current and the short circuit current have to be carefully calculated when designing the DC system, so that the circuit breakers or load components do not get damaged, when faults occur. Also the location and surroundings of the system have to be designed wisely, in order to avoid damage on humans, if accidents occur. (Hiekka 2012)

Depending whether using half or full bridge inverters, the DC voltage amplitude has to be at a certain level if for example AC voltage of 400 V is demanded. Here, when using a half bridge inverter the DC voltage has to be at least 800 V and with the full bridge inverter, at least 565 V. If AC voltage of 400 V is demanded and using a half bridged inverter, the distribution has to be unipolar, since the bipolar only supports up to DC voltage 750 V. The unipolar distribution is accomplished with one phase (2 lines) when the bipolar requires two-phase wiring (3 lines). (Voutilainen 2007: 23)

The conventional AC/DC bus system offers some advantages compared to either AC or DC bus systems. It can satisfy AC loads directly, unlike a DC bus system. Although, the DC bus for bigger PV systems with battery storage is more efficient. (Ross 2004)

4.4.3 Other components

The balance of system (BOS) includes all the wiring, fuses, combiners, grounding connectors, switchgear etc. These components have to be made of durable material, since they have to tolerate harsh weather conditions that would cause e.g. corrosion. All BOS have to be rated for correct voltage and current class and the wires also for special designations to be sustainable enough.

The frequency converter is a very important component in a wind power plant. It consists of a rectifier for converting the AC power to DC power on the generator side, energy storage (capacitor bank) in the middle and finally on the grid side an inverter which converts the DC power to AC power. The function of the frequency converter is as the name tells, to change the supplied AC voltage and frequency to desired level. There are different converter topologies, but the most widely used three-phase frequency converter is a so called back-to-back converter. The back-to-back converter is a bidirectional converter consisting of two pulse width modulated (PWM) voltage source controllers (VSC) and converters. The capacitor bank in between the two inverters allows decoupling of the control in order to not affect the other side when controlling the other. The rectifier has to be chosen depending on the generator. A diode rectifier can only be used together with a synchronous generator, while gate turn-off thyristor (GTO) and IGBT rectifiers have to be used with variable speed induction generators. The IGBTs have developed fast and are a better choice.

Soft starters are power electrical devices that reduce the in-rush currents when connecting the fixed-speed wind turbine to the grid. Without a soft-starter the in-rush current can be up to 8 times higher than the rated current, and may therefore affect disturbances in the grid. It contains two thyristors, whose firing angles are adjusted during the grid connection. After the in-rush the thyristors are bypassed in order to minimize power losses. The wind power plants have also capacitor banks, which are used for supplying reactive power to the induction generator in order not to absorb too much reactive power from the grid. The capacitor banks can also be disconnected depending on the reactive power demand of the generator. (Ackermann 2005: 72 - 75)

In PV systems the charging procedure is much more complex than in conventional battery chargers, since the current varies according to the solar insolation, also known as irradiance (Wh/m^2). The charge controllers with a maximum power point tracker (MPPT) are the most effective in these cases, since it measures the current, voltage or power from the PV generators and derives the voltage to be optimum for the battery system or the load.

The MPPT is an electronic device integrated in the converter for obtaining the maximum efficiency from the PV. It measures the voltage and the current that the panels generate and calculates the maximum point at which the current and voltage generates the highest power. It also acts as a breaker and cuts the connection if too big differences in between them are detected. The MPPT is also very useful when charging batteries, since it detects the optimal voltage level which should be used for the most efficient charging. Simulations and tests show that the charging time is significantly shorter compared to systems without a MPPT.

Figure 16 shows how the MPPT affects the power obtained from PV panels. There are three different lines for three different irradiance peaks (W/m^2) and the maximum power change depends on the voltage level that is used. (Messenger & Ventre, 2010)

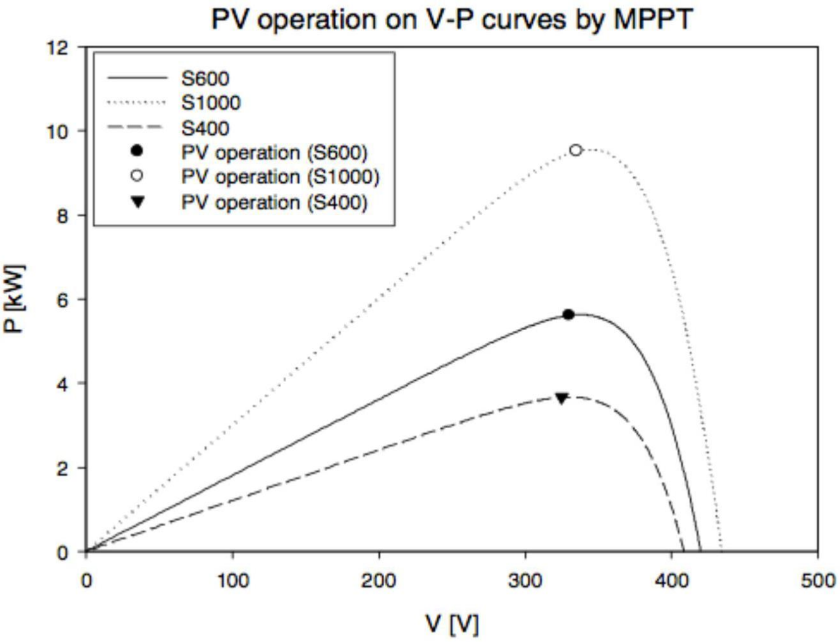

Figure 16. Power as a function of voltage with three different irradiances for a PV array connected to a MPPT. (Messenger & Ventre 2010)

The DC to AC de-rate factor for a PV system, in other words the power losses, can be calculated with a calculating tool on the Internet. Table 1 presents the different components that have to be taken into consideration when calculating the power losses. There are also suggested ranges of acceptable values for each of the component. The most affecting components are PV nameplate efficiency, inverter and transformer, soiling and aging. Shading is the most important of course, but since the possibility that it is cloudy is already taken into consideration in the insolation at the site, it is not needed to take into account in the DC to AC de-rate factor calculations.

Table 1. A calculating table for DC to AC de-rate factor for PV systems. (NREL 2012)

Component De-rate Factors	Component De-rate Values	Range of Acceptable Values
PV module nameplate DC rating	0.95	0.80 - 1.05
Inverter and Transformer	0.92	0.88 - 0.98
Mismatch	0.98	0.97 - 0.995
Diodes and connections	0.995	0.99 - 0.997
DC wiring	0.98	0.97 - 0.99
AC wiring	0.99	0.98 - 0.993
Soiling	0.94	0.30 - 0.995
System availability	0.99	0.00 - 0.995
Shading	1	0.00 - 1.00
Sun-tracking	1	0.95 - 1.00
Age	1	0.70 - 1.00

4.5 Control and automation system

Control is a key enabling technology for the deployment of renewable energy systems. Solar and wind power require advanced control techniques for high-performance and reliable operation (Camacho, Samad, Garcia-Sanz & Hiskens 2011).

As mentioned in Section 2.1. UNIC takes care of the automation and protection of the engine. The UNIC systems are connected to the PLC via Ethernet connection. The function of the PLC is to handle all the control in the power plant. With automatic voltage regulators the correct voltage level to the grid is controlled all the time. In a Wärtsilä hybrid power plant the renewable generation would also be controlled with the PLC. The challenge increases with several generating units and especially due to the fluctuating power generation of the renewable sources. Protection of the engines is handled with an engine shutdown circuit, which is protecting engine against over speed, over current etc. Protection relays handle the generator and switchgear protection. The different components for the automation and connections for telecommunication are shown in Figure 17.

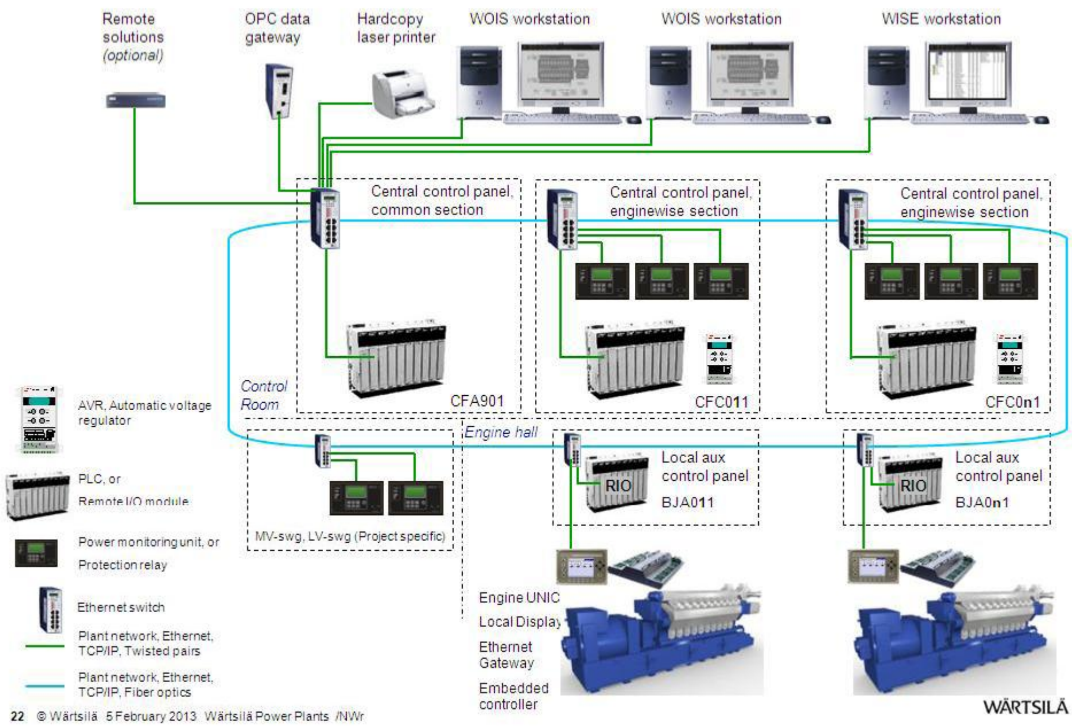

Figure 17. The advanced automation and its connections starting from engine embedded UNIC systems connected trough PLC modules and ending with Wärtsilä Operator Interface System. (Wägar 2012)

4.6 Energy storage systems

Finding an economical and effective storage system for islands is still a major challenge for the power sector. The renewable power generation is not reliable in load following. Therefore, a storage system would solve this problem by storing excessive energy when the power demand is lower. Storage options come in different sizes and types, pumped hydro for larger energy storage and batteries or flywheels for small projects under 100 MW. Besides the small generation in our case, the pumped hydro is not often feasible for small islands, due to need of fresh water and large land area. (EurElectric 2012)

In Table 2 is presented a comparison between pumped hydro, batteries, heat and flywheels as storage systems. The table shows e.g. the cost, efficiency and lifetime of the different storage systems. The energy storage investment (€/kWh) is clearly higher for batteries and flywheels and the lifetime is also much lower in comparison with pumped hydro and heat. Although, according to the reference, the lifetime of a heat storage system is unknown. However, ramp-up time is remarkably faster and also the efficiency is better for batteries and flywheels.

Table 2. Comparison of major storage systems (Klimstra & Hotakainen 2012)

KPI	Unit	Pumped hydro	Batteries	Heat	Flywheel
Energy storage investment	€/kWh	30 - 60	150 - 400	3 - 100	>500
Power-based investment	€/kW	750 - 1000	>1800	30 - 2000	>400
Turn-around efficiency	%	75 - 85	<85	70	90
Ramp-up time	s	15 - 60	instantaneous	2 - 100	2
Time-based loss	%/day	-	1 - 10	0.2	>5
O&M storage	% of the investment	<2	10	2	<3
Storage system life	years/cycles	100 years	>2000 cycles	?	5 years
O&M converters	% of the investment	5	10	3	3
Life converters	years	30	>10	20	?
Depth of discharge	%	90	50 - 80	50	50

4.6.1 Batteries

The cost efficiency of adding a battery system to the hybrid off-grid power plant is a difficult question. It has been discussed in several research studies and the opinions of its importance are divided. During the 20 - 30 years lifetime of the hybrid concept, the price of the battery system increases to 40 % of the whole power plant. Nevertheless, the reliability during peak consumption can be jeopardized if sufficient back-up power is not available. (Hyytinen 2012)

Batteries are consumed when they have less than 80 % of the rated capacity left. Even though the batteries can be used until 50 % of the rated capacity remains, it needs to be notified, that the power available from the battery will be reduced. Especially in hybrid systems the solar fraction decreases with reduced battery capacity. Also the aging batteries affect on safety, due to dangerous situations of battery breakdowns e.g. short circuit caused by corrosion.

If battery storage system is added to the power plant, lead-acid batteries are economically the best option, especially for larger systems, even though their lifetime is short. Lithium-ion batteries are best suited to autonomous power systems due to their technical parameters. Lithium-ion batteries are very expensive and thus their advantage may not be economically worthy yet. When planning the system, adding extra investment in battery function will lead to long-term savings, especially in case of frequent full charging and deep discharging protection. (Luque & Hegedus 2011)

Figure 18 shows a line diagram of a battery system connection. Batteries can be coupled in series to provide a higher voltage. When batteries are coupled in parallel the current I equals in this case to $I_1 + I_2$.

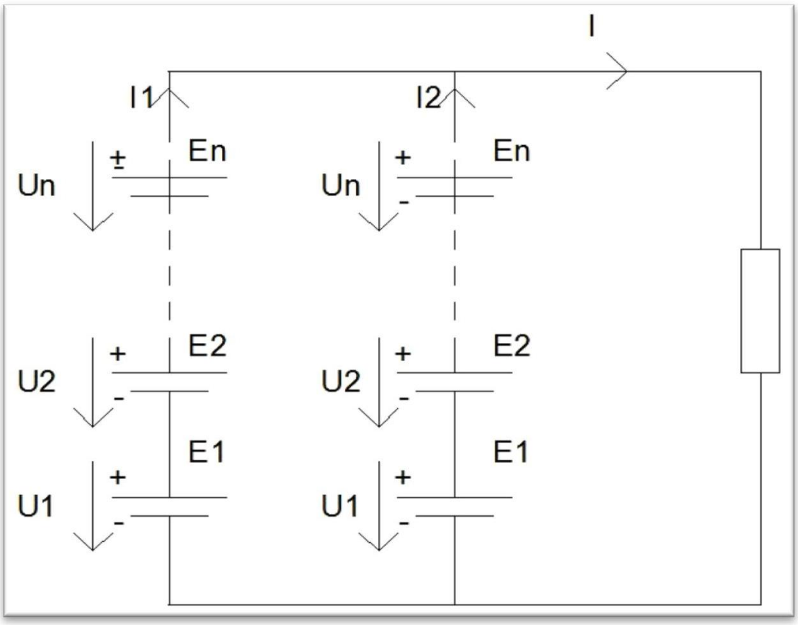

Figure 18. Line diagram of a battery storage system. (Hiekka 2012)

4.6.2 Thermal storage

When designing thermal storage systems, one has to know several important thermal properties of different materials. The most consequential is the heat capacity $C_{p,}$ which signifies the amount of heat that can be stored by a material. But one cannot choose the correct material without considering the other important properties, e.g. thermal conductivity, *k*, and thermal diffusivity, *D*. The thermal conductivity is a measurement of the temperature gradient through a material and the thermal diffusivity the speed of the heat transfer trough a material. There are also differences in cost and performance whether using a liquid or solid material. Solid material offers advantages such as, no concern about high-pressure containment, no energy input requirement for convection or cooling and lower system and operation costs. According to a study made by Sorrel et al. (2009) the best material for a thermal storage system at the moment is bulk graphite. It has the best overall performance for systems operating in less than 600 degrees in Celsius. (Sorrel, Palmer, Bowen & Nakaruk 2009)

Adding of a thermal storage system will only be profitable with CSP systems, since they generate heat directly from the sun energy and do not convert it to electricity before storing, unlike PV and wind power systems. Discussing the cost efficiency of storage system, only with high renewable penetration it will benefit, because of the reduced need of conventional high cost generation. (Hossein, Madaeni, Sioshansi & Denholm 2012)

In Cyprus a 50 MW parabolic trough system with a thermal storage is under construction. The thermal storage system is charged within 6 hours to full charge during summer, with hot fluid that the parabolic through system warms with sunlight. The thermal storage system can feed the load with electricity for 7.5 hours, if fully charged. Through a steam turbine the efficiency will be 38 - 39 % and the net electricity power output 39 MW in storage mode. Total investment cost for the 50 MW power plant is estimated to 360 M€. (EurElectric 2012: 35)

4.6.3 Flywheels

Flywheels are briefly reviewed in this thesis, because at the moment they are not considered suitable, since the goal is to utilise the generating sets with their stored fuel and possible battery system for a fast back-up and thus the flywheel would not be needed due to its capabilities and high cost.

The flywheel storage system stores mechanical energy in a spinning rotor, which is connected to an engine or generator. When the switch is off, the kinetic energy is released back to the engine and it will work as a generator. Flywheels are divided to low-speed and high-speed flywheels. Low-speed flywheels have a speed of less than 10000 rpm, while high-speed flywheels rotate with the speed of over 10000 rpm. In power industry the more common model is the low-speed flywheel. The advantage of flywheels is their capability to regulate the voltage ultra-fast. But then again because the generator is synchronised to the grid frequency, the flywheels are only used for varying the frequency, which limits the advantages of the flywheel. (EurElectric 2012: 35; Veszpremi & Schmidt 2007)

5 WÄRTSILÄ HYBRID GENERATION CONCEPTS

The goal of this thesis is to find an ideal share of renewable energy for small off-grid power plants (5 - 100 MW) or small grids (10 - 300 MW). The hybrid power plant will consist of several gas or liquid fuel combustion engines and a proper amount of either solar or wind power. These small off-grid power plants may be located on islands and due to good weather conditions to utilize renewable energy, this hybrid power generation concept study is made to be suitable for customers on islands in the sun-belt countries.

5.1 Choosing the hybrid concept

As mentioned in Chapter 3 the different renewable energy options all seem as good choices and there is no right or wrong solution, rather a chance to utilize the most efficient electricity production method for each individual location. Due to restricted land area in most of the cases, there are great opportunities to solve this problem by designing the power plant site thoroughly and thus finding space for the renewable energy system. That would most likely shorten the distances between the generation systems, and therefore making savings in cable costs. Also, using a DC-bus would make savings in cable costs.

5.1.1 Optimal Wärtsilä power plant setup

When selecting the optimal Wärtsilä combustion engine power plant for this hybrid concept, it is important to know what kind of a power plant is needed. In these kinds of cases it is normally a flexible base-load power plant, but it could also be a reserve or peak load power plant. Most important is the magnitude of the base-load and the peaks, but also the type of the load. There can be critical loads, which need to be kept running, or perhaps there is a huge variation in the load. In most of the cases and especially in off-grid solutions the adequate power supply is important. In cases where load shedding is possible, some arrangements can be made in critical situations. The selection of the optimal power plant is affected a lot by the customer needs and the possibilities in handling the load.

When choosing the amount of engines for a power plant the load magnitude and type has to be known as mentioned above. What also has to be taken into consideration is that there will always have to be at least n + 1 amount of engines, where n is the optimal amount, since one engine might be under maintenance or suddenly trip. With this information the optimal engine and amount of engines can be chosen.

Due to our restricted power plant size, less than 100 MW in this hybrid concept study, the optimal engine would be the 20V34SG gas engine or the 20V32 diesel engine because of the appropriate power supply. The 20V34SG generates power of 9730 kW and the 20V32 generates 8924 kW. Also, the 20V32DF dual fuel is a good option if there is no natural gas infrastructure yet on the site, but plans of building one later. The bigger the engine is the better efficiency it has. But in general, the more engines there are, the more reliable the power plant gets. If there are four engines and one trip, 25 % of the power supply is lost. But if there are eight engines with a smaller power generation and one trip, only 12.5 % of the supply is lost. Therefore, the 18V46 diesel engine and the 18V50SG gas engine are considered too big units for this concept, since their power generation are 17 MW and respectively 18 MW. The smaller engines are also easier to transport and to install. Table 3 presents the units and their power generation. It shows also the amount of engines to reach power generation of 100 MW, which gives a perspective of an ideal engine for this concept. (Wärtsilä 2012a)

Table 3. Comparison of suitable Wärtsilä combustion engines for this concept.

Unit	Power (kW)	Number of units to generate 100 MW
20V32	8924	12
20V34SG	9730	11
18V46	17080	6
18V50SG	18320	6

5.1.2 Choosing between solar and wind power

The question whether utilising solar or wind power is mainly depending on the weather conditions at the site, but also on the available land area, the local lifting craft and possibilities in general to build a renewable energy generation system. E.g. if the adequate weather conditions are better for utilising wind power than solar power and there is not enough free land area for required amount of solar power, the solution would be to invest in wind power. On the other hand, if the terrain is not suitable for erecting wind turbines, solar power could be better. There is also the option to invest in both solar and wind power. Wind is more comparable to a base-load power source because it can usually generate power 24 hours a day. Solar, on the other hand, generates power only during the daytime hours, making it a perfect peak power source.

We do not consider one source better than the other, though; in fact, it means they complement each other quite well. Depending on the location, the best solution might be to invest in both of them to minimize the loss of power supply, since seasonal variations in power supply from renewable sources occurs. It is more likely that in areas with much sun and wind (islands in the sun-belt region) either it is windy or sunny, and at least some of the renewable energy is available. (Khurshid 2011)

Good weather forecasting is important in improving renewable energy delivery to the grid. Also, when planning the system, weather forecasts are important in order to determine whether investing in solar or wind power. Of course the investment and operation & maintenance costs of the system play a big role when designing the optimal hybrid concept. Therefore, some calculations in Chapter 6 based on the costs of producing electricity with either wind or solar power are presented.

The available land area is also a critical factor to be taken into account when determining which renewable source to utilize. According to Denholm, Hand, Jackson and Ong (2009) typical wind turbine spacing in wind farms is placing the towers at the distance of 5 to 10 turbine diameters apart, depending on local conditions. In addition to that, every wind turbine needs a “footprint” area, which is around 1000 m^2.

Calculations of wind power plants total power production divided by total land area in tens of wind projects in United States of America was 2 - 5 W/m^2, depending on the project. The solar radiation on the surface of the earth in sunny areas during a year is around 6 kWh/m^2/day, which would generate a power of 250 W/m^2. Due to an efficiency of approximately 15 % for the PV system, the actual output will be 37.5 W/m^2. That is ten times more than for the wind turbines per square meter in average. So if the only issue with equal good weather conditions is the free land area, the PV array will generate more power than the wind turbines. What has to be taken into consideration is that the land area between the wind turbines is free for other use, e.g. for planting and also, that the investment cost for power generated with PV per square meter is much higher than with wind. (Denholm et al. 2009; Keffer 2010, Solar Electricity Handbook Website 2013; Klimstra & Hotakainen 2012: 62 - 64)

5.1.3 Ideal share of renewable energy

As mentioned earlier, the weather forecasting or actually the historical data of wind speed and solar irradiation is an important part of improving energy delivery to the grid. It is also beneficial when determining the amount of renewable power of the whole power generation system at the planning stage. If the weather conditions are seasonally poor, the combustion engines will have to provide the whole power demand if there is no storage system, therefore investing in a too big share of renewable energy will be inefficient at some point.

The solar power supports perfectly the high peak during the day, if it is not unfortunately cloudy. Wind power again, is harder to predict and it can blow during day or night, but if it is a windy site, the wind power is a good renewable resource to utilize. Adding of renewable generation will decrease the need of base load, and since Wärtsilä combustion engines are working as rapid starting intermediate load providers in these small off-grid solutions, they fit in a hybrid system combined with renewable power generation very well. So, in these cases if the location is sunny and windy, the ideal amount could be 10 - 30 % of both solar and wind, and adjustments in the percentage of one or the other according to weather conditions and site possibilities is considered.

If the combustion engine power supply is not calculated to cover the whole peak power demand and the renewable share grows to a much larger share of the peak power generation, the electricity supply might not meet the demand at certain times due to bad weather. Also, there will be a lower amount of spinning reserves for frequency controlling. Then more money must be invested in back-up power, if high reliability is essential.

5.2 Power plant own consumption

When operating a power plant there are always parasitic loads e.g. electricity consuming auxiliaries and functions, which are however necessary in order to keep the plant running. Even though the power plant is in stand-by operation, it still has some electricity consumption. Therefore, utilising the energy of the renewable sources for minimising the own consumption might be a cost reduction possibility for the power plant that is of great value. Different solutions are considered and the payback time is calculated.

The biggest differences in power plants' own consumption are the ambient temperature, having an impact on the electricity need for cooling and ventilation, and also the size of the engine. In following, the different consuming parts in a Wärtsilä power plant are presented.

Figure 19 shows the own consumption for different power plants, calculated with Perf Pro program. Perf Pro is an internal Wärtsilä tool used for performance calculations. It can use the estimated parasitic loads to get more accurate performance figures. A power plant consisting of ten 20V32 generating sets will consume around 2.6 % of the produced power at the ambient temperature of 35 degrees in Celcius, but only 2.25 % at the ambient temperature of 25 degrees in Celsius. Another big difference that can be seen is the consumption depending on the fuel type the engine is running on, due to no need of fuel heating, treatment or pumping in gas-driven engines. There can also be seen the different consuming parts and their share of the whole consumption in percentage. (Lindvall 2012)

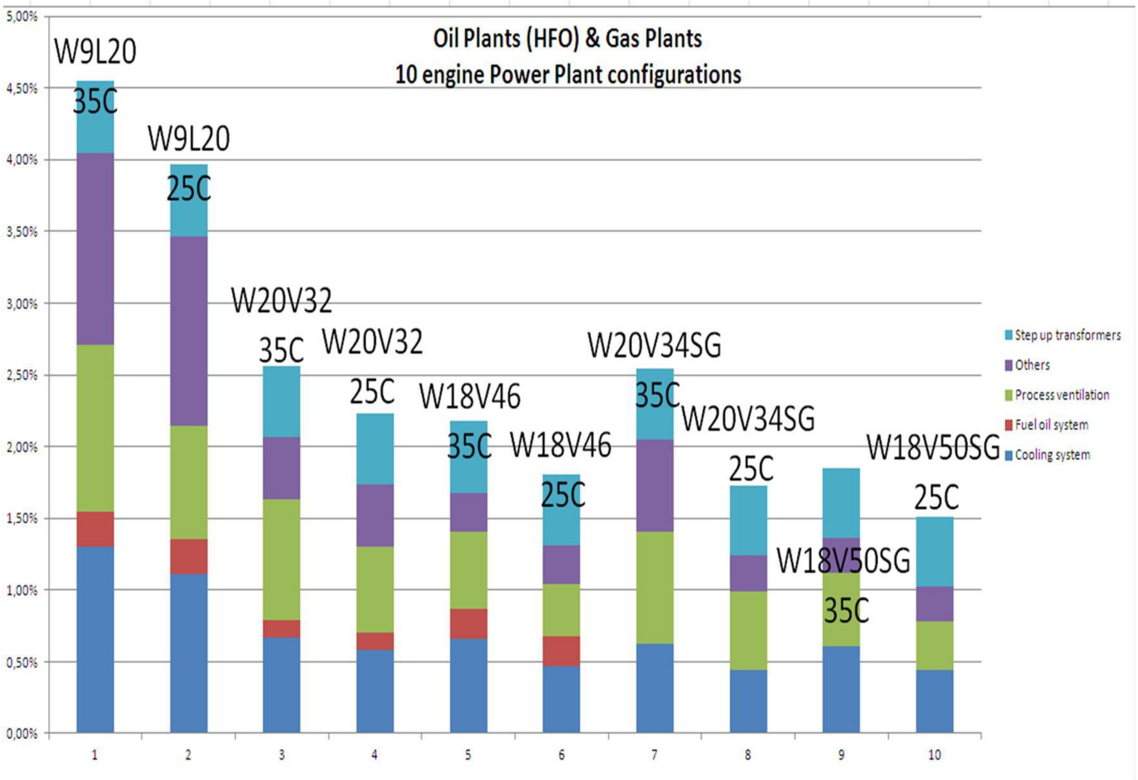

Figure 19. Own consumption in percentage for different engines at ambient temperatures of 25 and 35 degrees in Celcius. (Lindvall 2012)

5.2.1 Preheating of engine and fuel tank

The Wärtsilä combustion engines need to be in hot pre-heated mode to have a rapid start-up time of 1 minute. As an example, the continuous heating power required to keep a Wärtsilä 20V32 at 70 degrees in Celsius is 27 kW. If there are six 20V32 engines, the continuous electricity power demand only for preheating is 162 kW. Also HFO needs to be heated before pumping it into the engines, in order to get it enough liquid, due to its thickening in standard ambient temperature. The power required for pre-heating of the day fuel tank for a power plant of this size is around 57 kW.

5.2.2 Radiator cooling and ventilation

Radiators are electrically working fans where the engine coolant is cooled by a forced air flow. The radiator cooling system has no water consumption, therefore the power plant can be located anywhere. The drawbacks of radiator cooling is the slightly higher investment cost and power consumption compared to other cooling methods, although it is far more efficient than years ago, since it is connected through a frequency converter. The efficiency of electric motor is depending on the load, which should also be taken into consideration when calculating efficiencies.

The air condition consumes some electricity, especially in locations with higher ambient temperature. The heat losses from the engines, cables etc. also need to be ventilated or cooled in buildings, which increase the load on aircondition and ventilation units.

5.2.3 Electricity for automation and cooling

All Wärtsilä power plants have a DC back-up system for the automation and protection of the power plant. The batteries of DC system are charged continuously and therefore they consume some power all the time.

The lights of the power plant are also a consuming part, which is very seldom calculated. It is though understandable that the total power loss due to lighting is not a very high percentage of the whole consumption, but things like brightness outside, which is dependent of the time of year and location, affects this minor consumption.

Other electricity consuming parts in a power plant are fuel tank pumps for unloading the fuel, starting air system compressors, and for liquid fuel systems the electrically driven pumps which are used to transfer the fuel from the tanks to the engines and to increase the pressure before fuel injection. (Lindvall 2012)

5.3 Storage system

The necessity of a storage system is discussed and clearly a negative aspect in investing in it is the high cost and low lifetime. When running several combustion engines with renewable generation, the high part load efficiency and fast start-up and stop will regulate the power generation according to the load demand, thus making the fuel in the fuel tank as the energy storage system. Also, since combustion engines generate a high percentage of the total power, there is enough inertia for support of power quality. For minimising own consumption in hot stand-by power plants with a CSP system, the adding of a thermal storage would guarantee the hot pre-heating mode during night time.

If a customer necessarily wants a battery storage system, Lithium Ferro Phosphate (LFP) batteries are considered suitable for this kind of back-up system for Wärtsilä power plants. When there are peak loads or possibly a blackout, the proper sized battery system, 2 MWh for hybrid power plant concepts at this size, can provide power to the load for the first 10 minutes, until the combustion engines are started and are fully running. As mentioned in Section 2.4.1 the Wärtsilä combustion engine will start in 30 seconds and generate full power in just 5 minutes in preheated mode. (Wärtsilä 2012c)

6 CONCEPT EXAMPLES

For determining the optimal hybrid power plant and the share of solar and wind power, we chose to use PLEXOS® power system optimizer software, due to its special features in solving all the details of engine start-ups, fuel intake, fuel costs etc. The use of PLEXOS® makes it easy to compare several hybrid power generation concepts with different share of renewable generation.

These hybrid power generation concepts are made to be suitable for customers in Caribbean and other islands in the sun-belt region. Also, industrial and rural areas in the Middle East, with a lot of sun, are in the focus of Wärtsilä. Therefore, the weather data for the calculations are taken from Aruba from the past 5 years. The weather conditions are then scaled to fit the other possible locations with less wind or sun.

6.1 Calculations with PLEXOS®

The size of hybrid power plant in this thesis was determined to be 10 - 100 MW. Therefore, we chose eleven 20V32 diesel combustion engines for this simulation. The supply would have to cover the whole load, if the weather conditions were very bad and the renewable power generation at zero. The peak load in this simulation is scaled to 97.9 MW. We chose to exclude the simulations with the gas engine since the difference in results would not be that divergent. Moreover, the liquid fuel engine is mostly used in these areas.

Jyrki Leino, Senior Power System Analyst working for Wärtsilä helped me to simulate these scenarios with PLEXOS®.

6.1.1 Features in PLEXOS®

In PLEXOS®, a product of Energy exemplar, modelling of a lot of different scenarios is possible, due to a lot of features. In following some of the features are listed (Energy exemplar 2012):

- Power market simulation including day-ahead and real-time markets,
- Energy and ancillary services price forecasting,
- Detailed operational planning and optimization of unit commitment,
- Fuel and emission constraint management,
- Strategic modeling and decision support,
- Generation and transmission capacity expansion planning,
- Renewable generation integration analysis,
- Co-optimization of ancillary services and energy dispatch, and
- Generation portfolio optimization and valuation.

Figure 20 presents a view of the PLEXOS® result layout. There can be chosen a lot of different results to view, i.e. supply curves, fuel off-take, units generating, emission or waste heat values.

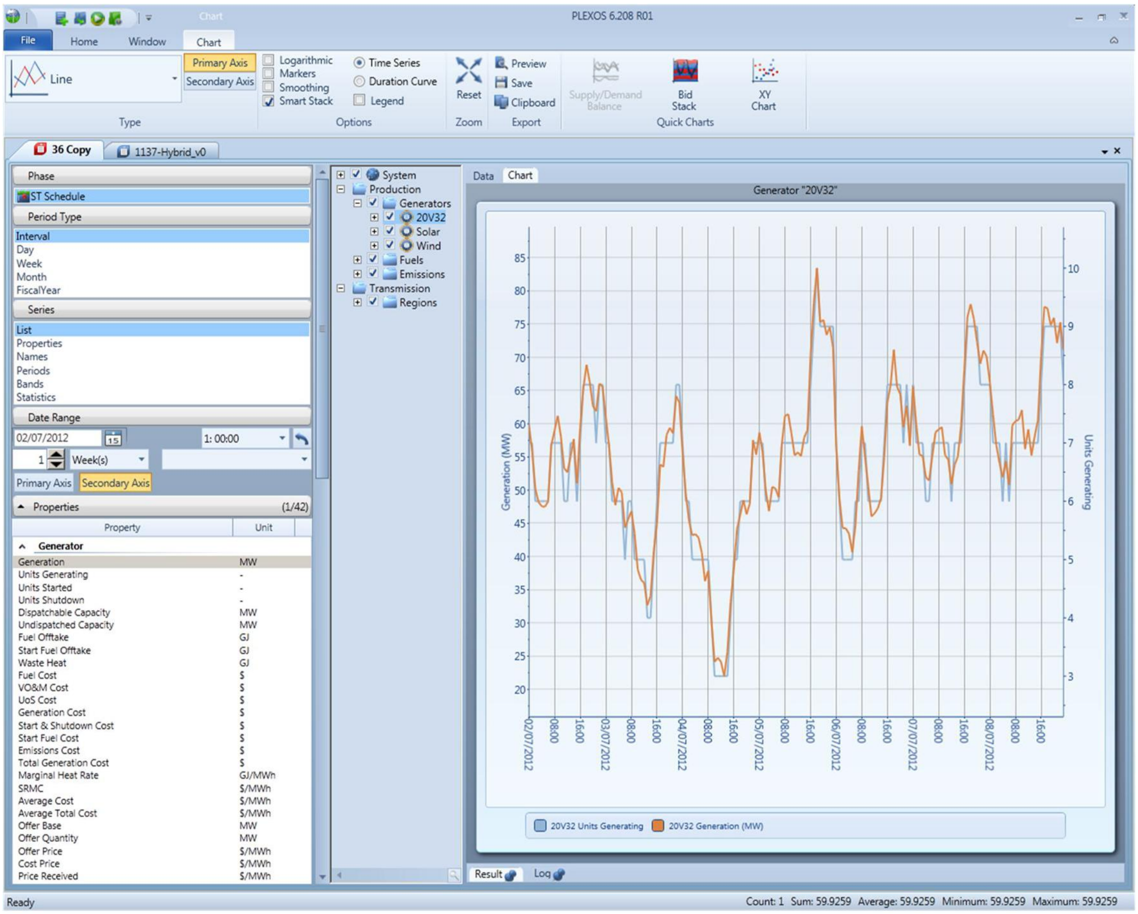

Figure 20. Screenshot of PLEXOS® power system optimizer programme.

6.1.2 Inputs

First wind and solar data from Aruba, an appropriate country for this concept, was collected and the power generation was also determined with the help of equations, factors and given results. In Aruba the average wind speed was 7.6 m/s and the average solar radiation 6 kWh/m^2/day. (National Oceanic and Atmospheric Administration; Solar Electricity Handbook Website 2013) For this simulation 2 MW wind turbines were chosen, due to its suitability for hybrid concepts of this size. The cut-in speed and generation at a particular wind speed was calculated with a typical wind speed formula for 2 MW wind turbines. Then by using PLEXOS® software the combustion engine set with different renewable penetration was simulated.

Two different types of hybrid power plant operations were chosen according to the load. The first one is mainly for regular customers on islands in the sun-belt region and the second one is for industrial sites where the load is more or less constant during a day. These two different operation types are recognized from the results as fluctuating load and stable load.

The cost of a PV system is typically given in price-per-peak-watt. Peak watt is defined as the power at standard test conditions (solar radiance 1000 W/m^2 and temperature 25 degrees in Celsius). PV system cost includes both module and BOS costs. The modules represent only 40 - 60 % of total PV system cost. The installation cost may vary significantly depending on the location due to site preparation, assembly labour and permit costs. (PVresource 2012)

Investment cost for wind power and PV production was found with several references. For wind power the investment cost was estimated to be 1100 - 1800 €/kW installed capacity, including connection costs, for example frequency converters. For PV the cost was estimated to 2000 - 3000 €/kW installed capacity, including BOS. Therefore we chose the average cost and used 2500 €/kW for solar and 1500 €/kW for wind in the calculations. Fuel costs, which will function as OPEX in the simulation, for a Wärtsilä 20V32 liquid fuel combustion engine is calculated to 13 €/GJ, which gives around 47 €/MWh generated energy. The fuel price was taken from an internal report and the newest fuel price (02/13) for HFO in Caribbean area was 496 €/ton. The investment and fuel costs can also easily be changed for the future, where most likely these costs are changing a lot, especially the PV investment cost. Other O&M costs were calculated to be more or less the same for the renewable systems as for the combustion engines. The O&M costs are also not that high in comparison with investment and fuel costs, so they could be ignored. (Nitsch, Pregger, Scholz & Naegler 2010; National renewable energy laboratory 2012c; MacDonald 2010).

6.1.3 Short term run

In PLEXOS® power system optimiser software the values are given in Excel and there is a profile made for each value. Then by giving multiples for these profiles, the inputs will change and the output results as well, when simulating with PLEXOS®. For the combustion engine profiles Wärtsilä has values which have been in use in previous cases and that made this simulation a whole lot easier.

For both stable and fluctuating load four different "locations" were chosen. The different locations were determined by choosing two rating factors for both. For solar 100 % and 75 % of the peak radiation and for wind 100 % and 70 % of the peak wind speed were chosen. In other words, the solar and wind values were scaled down to 75 % and 70 % from the peak to simulate locations with worse weather condition. This combined with the yearly wind and solar data gave a capacity factor of 29 % and 20 % for wind and respectively a capacity factor of 23 % and 18 % for solar. Capacity factor is the ratio of a generation system's actual output during a period, to the energy it would produce at full capacity during same period. According to National renewable energy laboratory (NREL 2012b) these are typical capacity factors for wind and solar power in the suitable areas for our hybrid concept.

After determining the capacity factors, different scenarios for these locations were calculated with 0 MW, 10 MW and 30 MW wind penetration, and the same for solar. All the scenarios were combined and altogether 72 different scenarios were simulated. Payback time results for only 64 combinations are shown due to the pointlessness of showing scenarios with zero penetration of renewables.

Figure 21 describes better the different scenarios mentioned above. The numbers from 1 to 72 are just to support when combining the scenarios after the simulation. The scenarios with zero penetration of renewables are highlighted.

Stable load

		WIND					
		70 %, peak			100 %, peak		
SOLAR	MW	0	10	30	0	10	30
100 %, peak	30	31	32	33	34	35	36
	10	25	26	27	28	29	30
	0	19	20	21	22	23	24
75 %, peak	30	13	14	15	16	17	18
	10	7	8	9	10	11	12
	0	1	2	3	4	5	6

Fluctuating load

		WIND					
		70 %, peak			100 %, peak		
SOLAR	MW	0	10	30	0	10	30
100%, peak	30	67	68	69	70	71	72
	10	61	62	63	64	65	66
	0	55	56	57	58	59	60
75 %, peak	30	49	50	51	52	53	54
	10	43	44	45	46	47	48
	0	37	38	39	40	41	42

Figure 21. Different locations and scenarios numbered for stable and fluctuating load cases.

6.2 Results

The simulations with PLEXOS® software gave a lot of different results. In this chapter the most interesting supply and engine performance curves are shown. Also, the payback times for different scenarios and the optimal power generation set-up are presented.

Figure 22 presents the supply curves for solar, wind and 20V32 engines during a day. It can be noticed that during noon the solar produces its peak and the engine generation decrease. Due to peak consumption during noon, the drop of the engine generation is not so big, just around half of the solar peak production. On Y-axis the power generation in megawatts and time on X-axis presented.

In hourly observations the wind or solar power generation are not zero. Thus, the amount engines could be less, for savings in investment cost. At the same time on minute level there can be shortages in power supply and power delivery to the grid has to be ensured during all time. Therefore, without a fast responding storage system or load shedding the peak power demand has to be covered solely with combustion engines.

Figure 22. Power supply curves during a day for solar, wind and the 20V32 engines with a fluctuating load and wind speed and solar radiation at 100 %.

In Figure 23 is presented the fluctuating load case with 30 MW penetration of both solar and wind, in the scenario with 100 % of peak for solar radiation and wind speed, during a summer week. The difference between night and day is seen as well as in Figure 23, but in Figure 24 is the difference between weekdays also seen. During weekends, especially on Sundays the peak load does not reach the level of the weekdays. At lowest only around 25 MW is generated with engines.

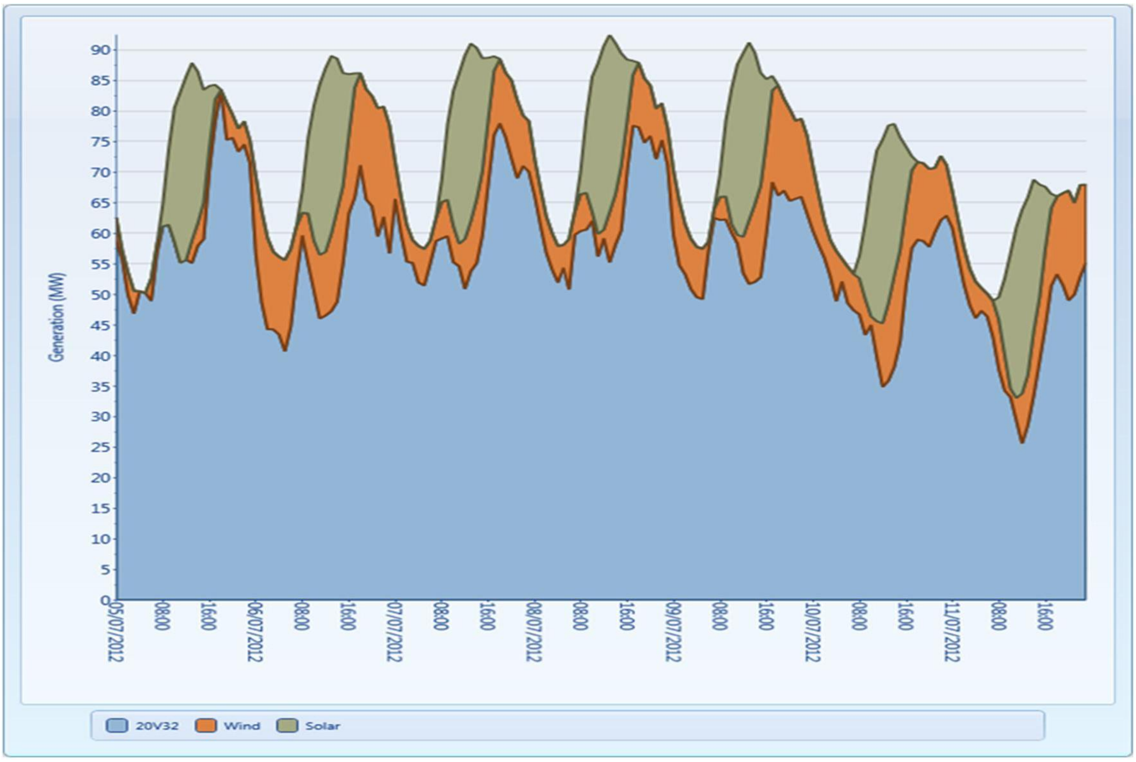

Figure 23. Fluctuating load case with 30 MW penetration of both solar and wind in the scenario with 100 % of peak for solar and wind, during a summer week.

Figure 24 shows the supply curve for the stable load case, with wind and solar penetration of 30 MW in the scenario with 100 % of peak for solar radiation and wind speed. An interesting thing seen in Figure 24 is a couple drops in the middle of the week where the power demand cannot be supported. Apparently due to poor weather conditions when solar and wind did not generate at all power. Since, the peak demand was set to 100 MW and the engines only generate 97.9 MW, there is undersupply of a couple MWs.

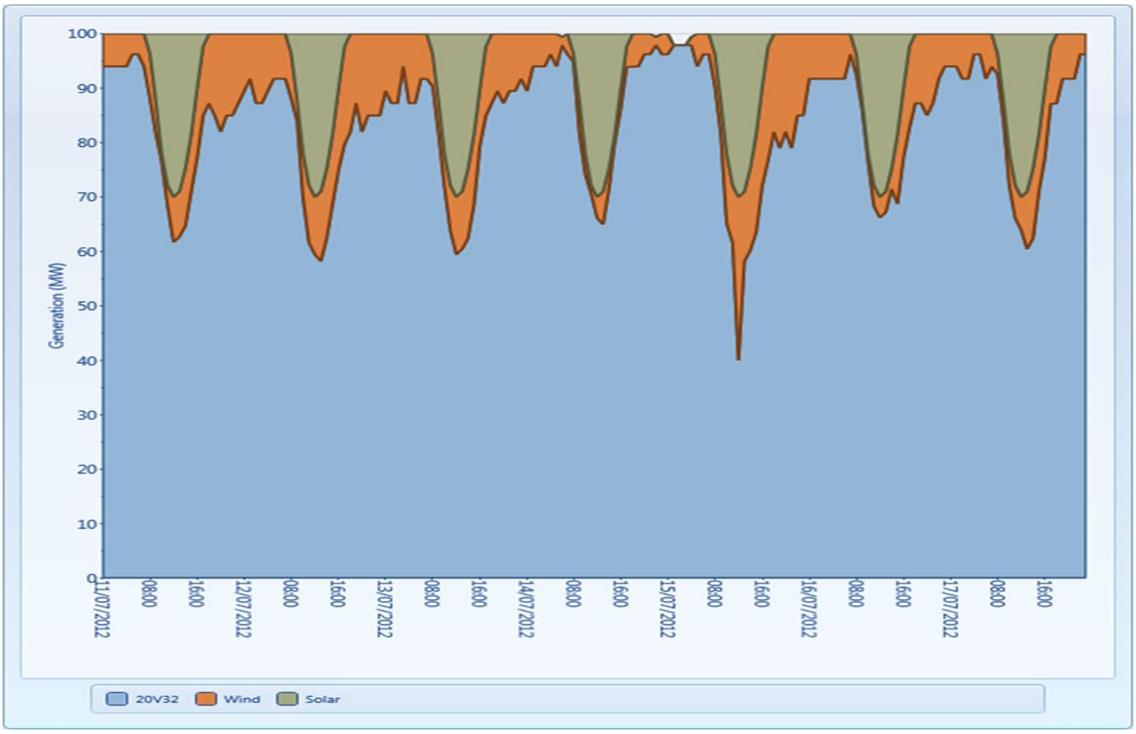

Figure 24. Stable load case with 30 MW penetration of both solar and wind in the scenario with 100 % of peak for solar and wind, during a summer week.

A very interesting feature that can only be determined in advance by using the PLEX-OS® software is shown in Figure 25. Depending of e.g. the load, fuel cost and start-up cost, the optimal amount engines running at a particular time can be determined. This is a situation with a fluctuating load, where the solar radiation is 100 % and the wind speed 70 %, and both solar and wind penetration 10 MW. The lack of power supply from the renewable sources will make all the engines run, in order to provide the customer power demand. Another thing worth mentioning is that the use of a storage system in our hybrid concept is unnecessary, since the fuel tanks combined with fast responding combustion engines work as a storage system. It can also be noticed that during summer months the amount engines running is lower, due to better generation from the renewable energy sources, especially solar.

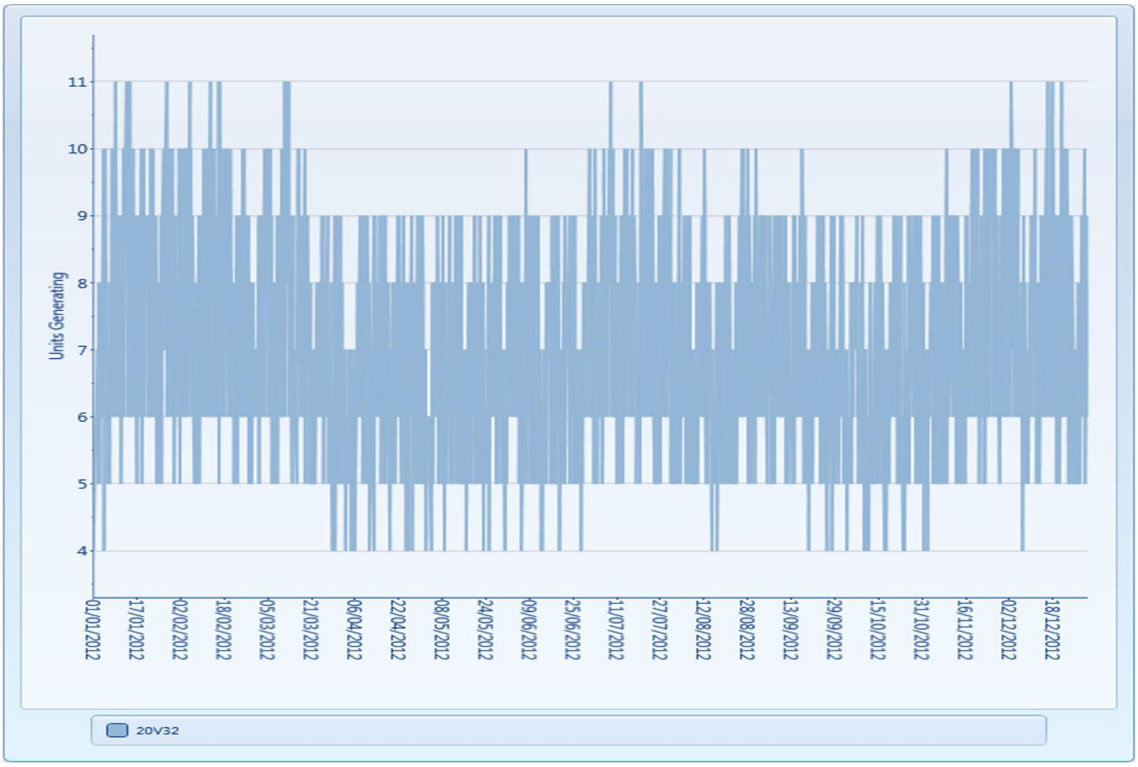

Figure 25. Number of units generating during a year with a fluctuating load. On Y-axis is the amount of units generating and on X-axis is time presented.

6.2.1 Payback time

Payback time refers to the time it takes for an investment to return the sum of the original investment. The time is usually measured in years, depending on the investment type. (Williams 2012)

The simplified payback time was calculated by subtracting the yearly winnings in reduction of fuel consumption from the investment cost of renewable power generation system. The interest rate was not taken into account when calculating the simplified payback time. Variety in time is quite large as can be seen in Figure 26. The suitability of the renewable power generation for fluctuating load is seen with clearly lower payback time from scenario 33 to 64 on X-axis. Altogether the payback times for these simulations are relatively short. With high fuel price and good weather conditions the money invested in renewable generation is gained easily during the systems lifetime of 20 - 30 years.

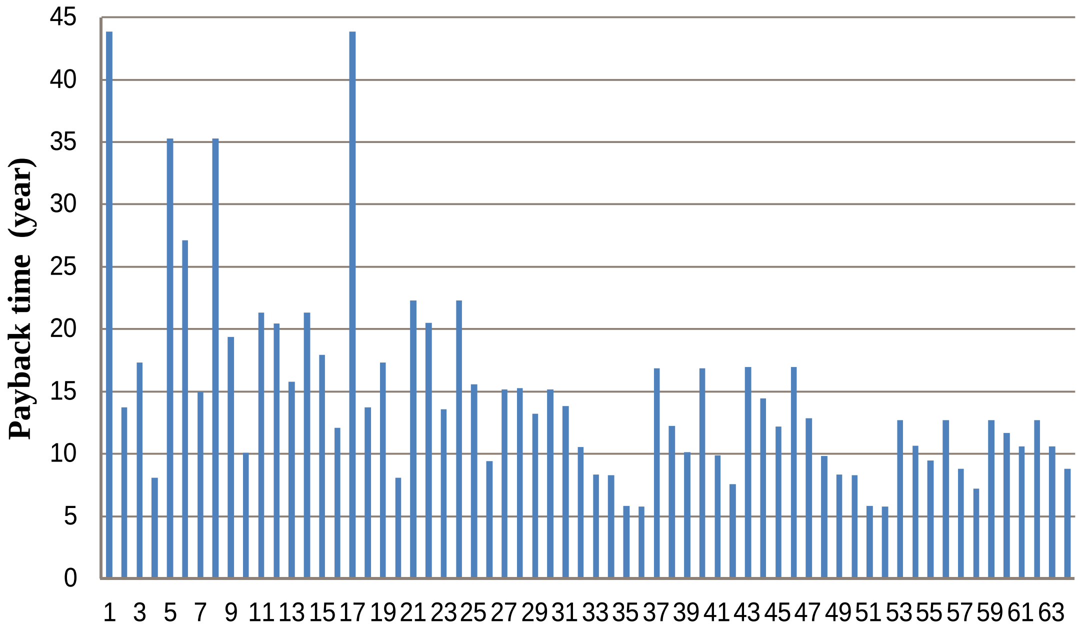

Figure 26. The simplified payback time for all simulated scenarios and locations presented. Payback time in years is shown on the Y-axis and on the X-axis are the numbers 1 – 64 shown to indicate the different scenarios at different locations as mentioned in Section 6.1.3.

The payback time graphs below are divided into the different locations as mentioned in Section 6.1.3 in order to more easily compare the different scenarios. The first location, presented in Figure 27, is the sunny and windy location, with 100 % solar radiation and wind speed. In this section there are presented four payback time graphs. First, each graphs for three locations with a fluctuating load and then one graph for a stable load. The results from the location with 75 % solar radiation and 70 % wind speed are not reviewed, due to no interest of investing in renewable power on a location with weather conditions not enough profitable. The markings on X-axis are the scenarios with invested in different amount of renewable power generation. S stands for solar power, W for wind power and the number for each is peak generation in megawatts, e.g. S0W10 stands for 0 MW solar power and 10 MW wind power. It is seen in the graph that investing in 10 or 30 MW wind power and not in solar at all, will give the shortest payback time, only 5.8 years. The price of PV panels is still higher than the price of wind turbines and therefore there is the big difference in the payback time.

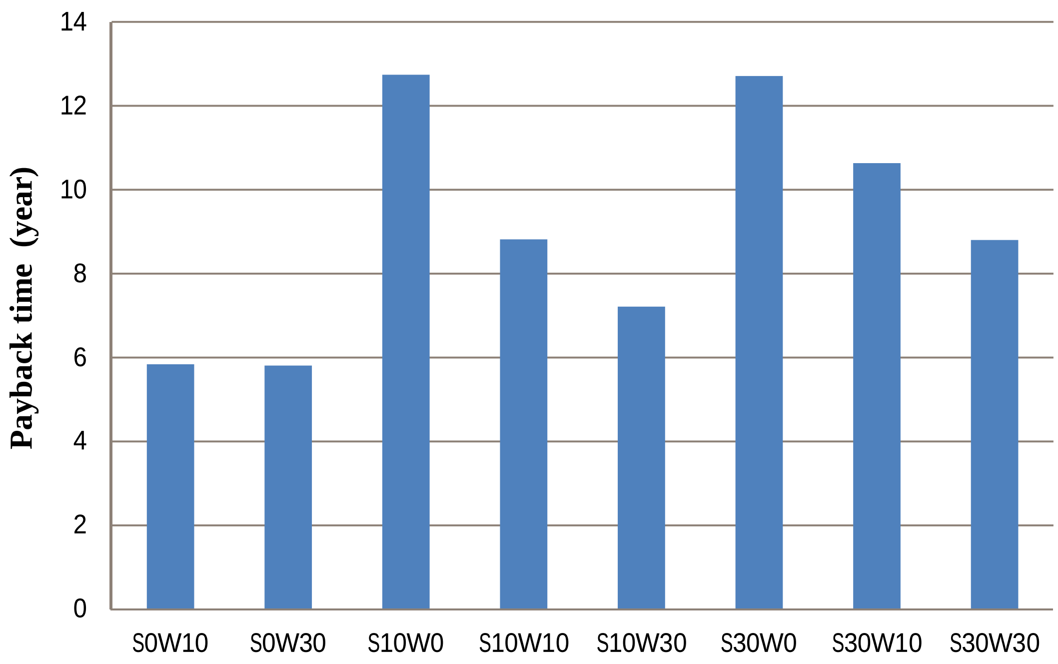

Figure 27. Payback time for different fluctuating load scenarios with both wind speed and solar radiance at 100 %. On Y-axis is the payback time in years and on X-axis are the different scenarios with different renewable penetration presented.

When the wind speed is reduced to 70 % but solar radiation is at 100 % the payback times do not differ so much. Still, investing in wind is more economical than investing in solar. If investing in both, due to daily and seasonal shortages, the scenario with 10 MW solar power and 30 MW wind power would have a relatively low payback time, 9.5 years. Results for these scenarios with different penetration in megawatts of solar power and wind power are shown in Figure 28.

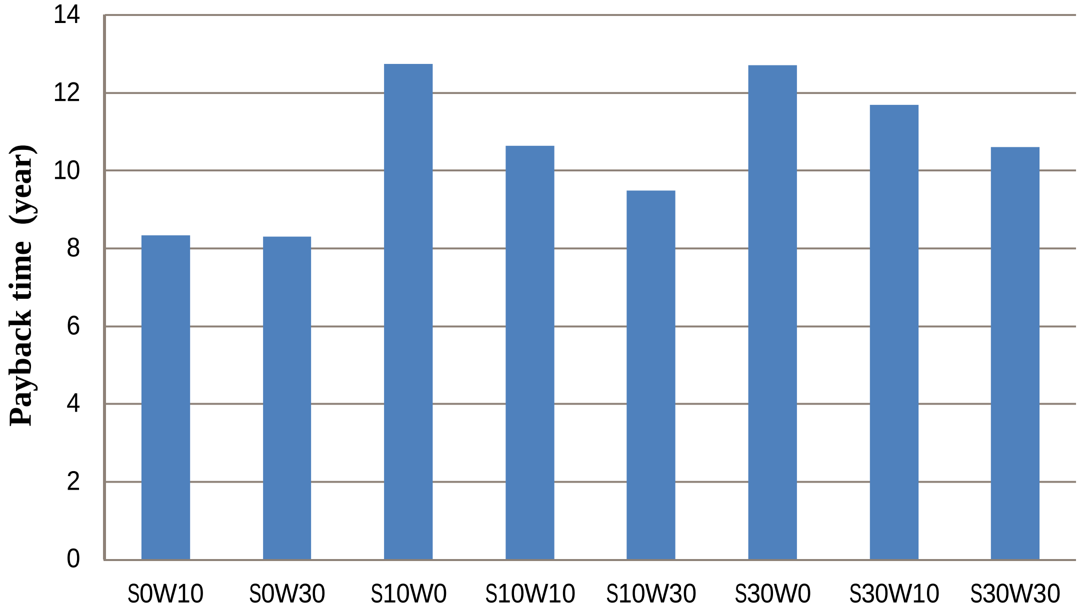

Figure 28. Payback time for different fluctuating load scenarios with 100 % solar radiation and 70 % wind speed. On Y-axis is the payback time in years and on X-axis are the different scenarios with different renewable penetration presented.

Figure 29 shows the biggest differences in the payback time, 17 years versus 5.8 years. The windy but not so sunny location, 75 % solar radiation and 100 % wind speed, clearly points out the benefit of investing in wind power.

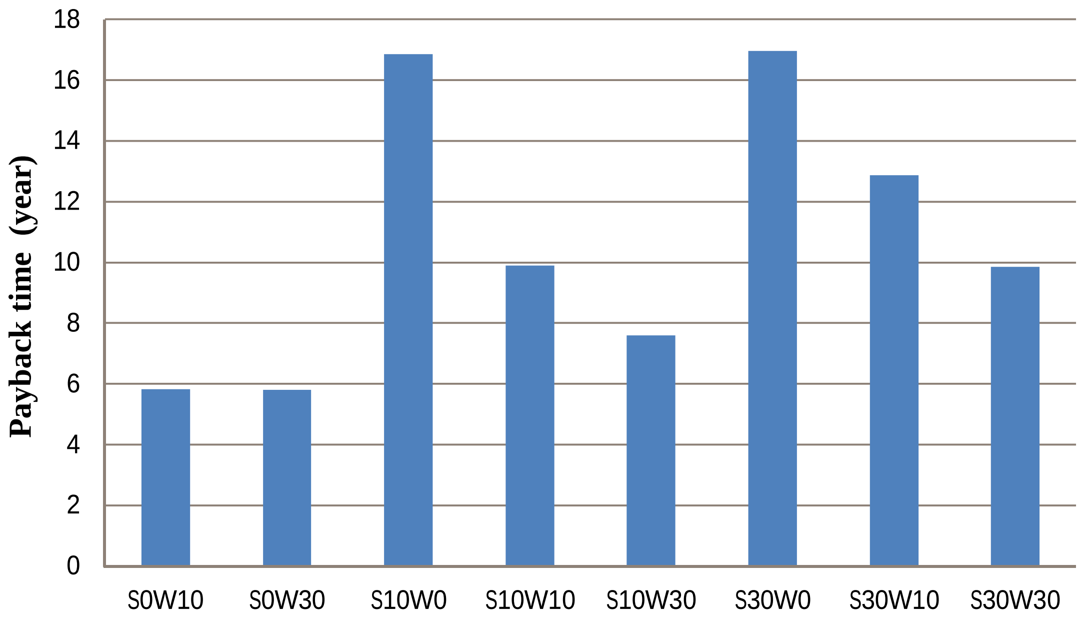

Figure 29. Payback time for different fluctuating load scenarios with 75 % solar radiation and 100 % wind speed. On Y-axis is the payback time in years and on X-axis are the different scenarios with different renewable penetration presented.

For stable load cases it was assumed that the power plants are located in areas with more sun and less wind i.e. on industrial or rural sites. Therefore, the payback time was calculated with 100 % solar radiation. It is also most likely that they are not located at coast and therefore, due to long distances with high cable cost and power losses, the wind power was excluded from these graphs. A huge drop in payback time from 22.3 to 15.2 years for 10 MW respectively 30 MW installed solar power is seen in Figure 30.

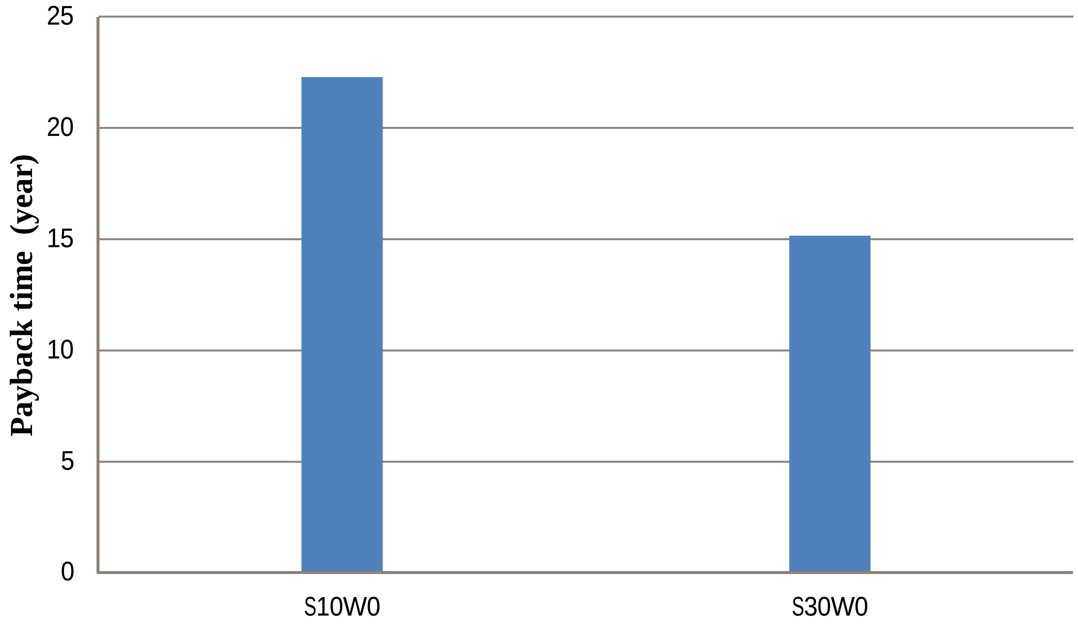

Figure 30. Payback time for different stable load scenarios with 100 % solar radiation. On Y-axis is the payback time in years and on X-axis are the different scenarios with different renewable penetration presented.

6.2.2 Ideal set-up

The ideal set-up is difficult to determine. According to payback time, the best set-up for fluctuating load cases would be 10 or 30 MW wind and no PV at all, even if the weather conditions are sunny, but not so windy (solar radiation 100 % of peak and wind speed 70 % of peak). But when taking into account the declining price of PV panels, the interest to invest in them arises, especially in the sunny locations. Besides, there might not be possibilities for erecting wind turbines. In that case solar power is the renewable generation to invest in. If investing in wind, the larger amount, 30 MW, is still a better choice than 10 MW, due to lower payback time and less money spent on assembly in proportion to the power generated. If investing in both wind and solar power, 10 MW solar power would be sufficient with today's investment cost according to the results. It would have been interesting to simulate with a larger amount of renewable generation and see at what point the investment in excessive renewable power would be worthless, due to lower power demand than power supply.

Taking a look again at the payback times, depending on how much the customer is willing to invest, and also the weather conditions and possibilities at the site, the ideal set-up could be 30 MW wind power and 10 MW solar power, besides 97.9 MW engine power output. Totally, the power plant generates 137.9 MW at peak if the power demand arises. This set-up at the location with solar radiation and the wind speed at 100 % of the peak, gives a payback time of 7.2 years, and with the wind speed reduced to 70 % a payback time of 9.5 years. In Figure 31 are the ideal set-up of power generation and the peak generation percentages shown.

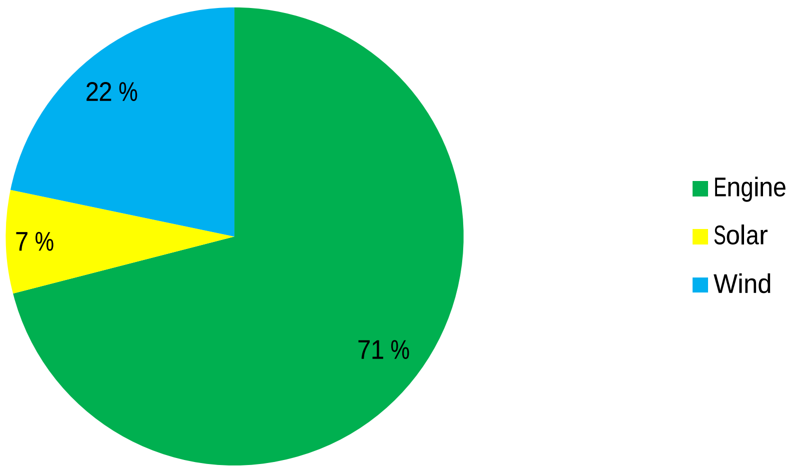

Figure 31. Ideal set-up of power generation for a fluctuating load, with different share of power generated by the engines, solar and wind.

For stable load the set-up is a bit different as mentioned in Section 6.2.1. When looking at the payback time graph, investing in 30 MW solar power instead of 10 MW will shorten the payback time from 22.3 years to 15.2 years. The peak power generation would be 127.9 MW, but due to stable load, the peak is still 100 MW but the power generated with the combustion engines is decreased to 70 % of total at peak solar radiation times. With the maximal power output the share would be 77 % engine power and 23 % solar power. This set-up from the scenario with 100 % solar radiation is presented in Figure 32.

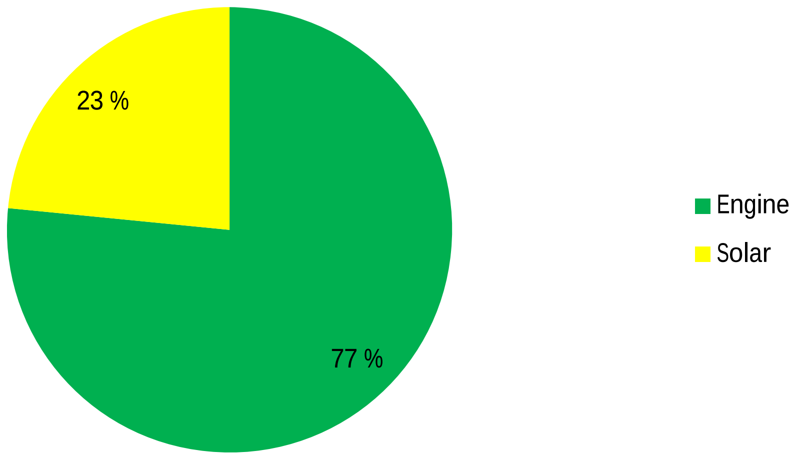

Figure 32. Ideal set-up of power generation for a stable load, with different share of power generated by the engines and solar.

6.3 CSP trough system for minimising own consumption

According to Cabeza, Sóle, Castell, Oró and Gil (2012) the efficiency from solar to electricity is only 15 - 20 % in existing solar thermal power plants, when again the thermal storage efficiency is up to 97 % at a temperature of 400 degrees in Celsius. Due to that we choose to not convert the energy of the sunrays directly to electricity, but instead using it to heat up a fluid and use that for heating of the engines and the fuel day tank. Together they consume at least 2/3 of the whole own consumption. The suitability of the CSP and thermal storage system for reducing own consumption in stand-by power plants is the reason why we only take that concept into consideration. Also, there is a necessity of a storage system for this concept. Since, the power plant might not be running during night, then pre-heating is needed at that time and there is no power generation from the CSP. The storage system will decrease the price of the CSP system, since a thermal storage system is a lot cheaper than a conventional battery storage system.

One advantage thermal collectors have unlike photovoltaic cells, is that thermal collectors absorb radiation from the entire solar spectrum. Therefore, solar thermal plants can utilize both the direct and diffuse solar radiation. (Cooper 2008)

The thermal storage is a key component if dispatchability is required. As can be seen in Figure 33 the thermal storage lengthens the power supply, and for how long time depends of the size of the thermal storage. The benefit of collecting diffuse radiation with CSP is also seen in the figure.

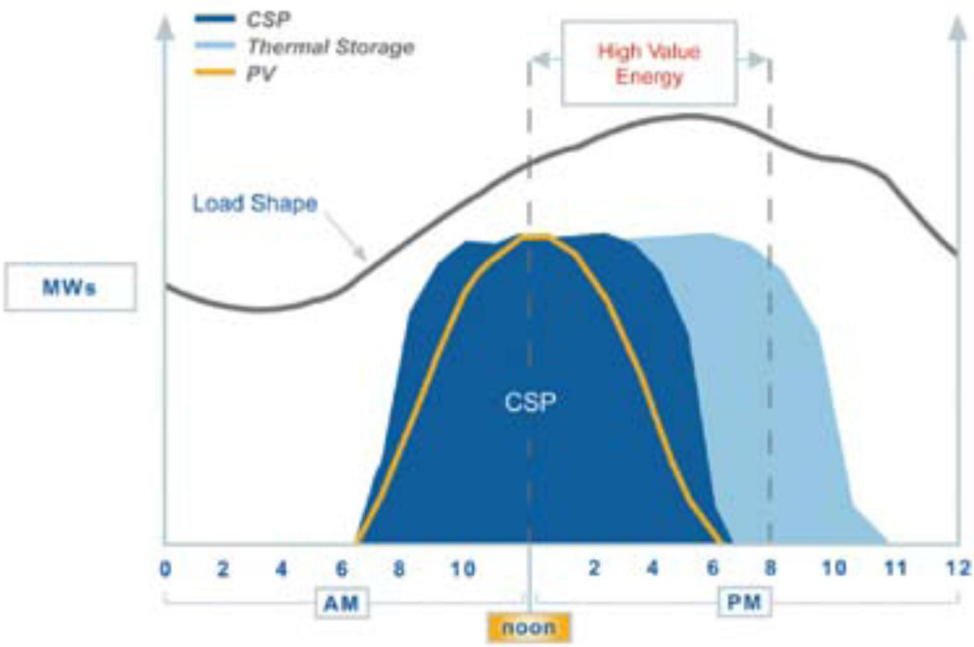

Figure 33. Comparison of power generation between PV, CSP and thermal storage during a day. (The Energy Industry Times 2013)

Figure 34 presents a simple closed system for pre-heating of the engines and the fuel day tank. The parabolic trough system heats the fluid up to 220 degrees in Celsius and it circulates between the troughs, buffer storage, and the object that is heated, in our case it would be the engines.

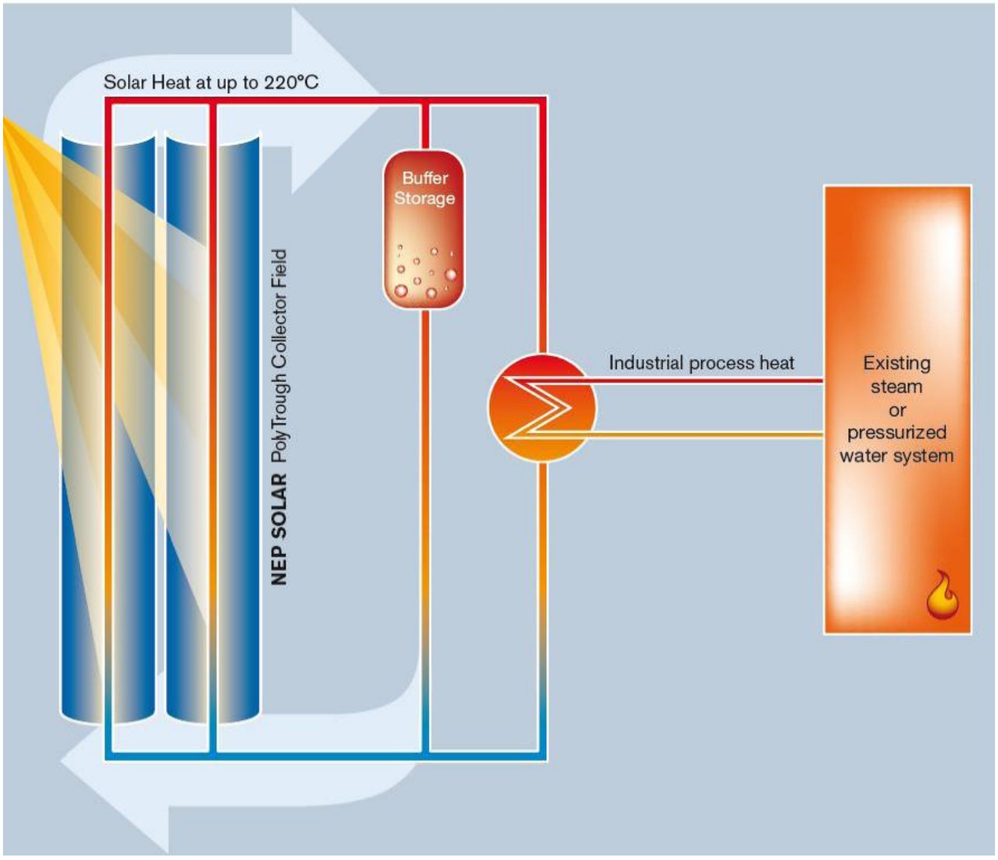

Figure 34. CSP troughs in a closed system for industrial process heating. (Nep solar 2012)

6.3.1 Calculations of energy consumption and investment in a CSP system

The calculations for the pre-heating was made for six 20V32 liquid fuel combustion engines with help of Perf Pro performance calculating tool. The pre-heating and day tank coil heater time was estimated to be 2/3 of the time during a year. In other words, the power plant is running 1/3 of the time during a year. During that time there is no need for pre-heating, except of the thermal storage system.

The calculations for the CSP system and solar radiation were made with values from the CSP distributor, Nep Solar, from an actual case in Amman, Jordan. The OPEX cost for pre-heating and the day tank heater coil were calculated with average heat generation values from Nep Solar and a LFO fuel price of 0.80 €/liter.

6.3.2 Results

Table 3 shows all the energy consumption results, and also the capital expenditures (CAPEX) and the operational expenditures (OPEX) for the systems. The calculations for engine and day tank heating was done by adding all energy consumption and calculated the fuel consumption (OPEX) for the same amount of energy produced with heaters. Then the investment cost for an adequte CSP system (CAPEX) was calculated. When knowing OPEX for the CSP and subtracting it from the OPEX for fuel consumption, total OPEX is obtained. Then the CAPEX for both CSP and thermal storage is divided with the total OPEX and the result is the payback time in years.

Table 3. Calculations for own consumption and payback time of a CSP system.

Unit	Power (kW)	Annual energy (MWh)	OPEX (€)	CAPEX (€)	Payback time (year)
Day tank coil heater	56.9	332.4	23269	-	
Pre-heating of engines	162.0	946.1	66226	-	
CSP system (incl. equipment)	145.9	1278.5	10000	576000	
Thermal storage (incl. equipment)	-	-	0	100000	
					8.5

The area, which the CSP system generating continuous power of 145.9 kW will require, is approximately 3600 m^2, and that is a quite large area to find on a power plant site that is already constructed. Nevertheless, there can be found free space on i.e. rooftops of the buildings. A Wärtsilä power plant site has plenty of buildings where space on rooftops is available, block transformer, engine auxiliary transformer, common auxiliary transformer shelter, fuel treatment house etc.

The payback time of 8.5 years seems as a decent investment, since the lifetime for a combustion engine power plant and a CSP system is around 30 years. One thing that has to be taken into account is the declining electricity spot-price during night. If the power plant is in stand-by mode often during night, the benefits of applying the CSP system will not be that high. Another thing is that most of the stand-by power plants are running more than 1/3 of the time during a year, which likewise lowers the profitability of the CSP system.

The average power production of the CSP during a year is 145.9 kW, which means that on a summer day the power generation will be much higher and especially if the engines are running, there will be a lot of excessive energy from the CSP system. Utilizing that energy in something else to lower the own consumption will increase the efficiency additionally.

7 DISCUSSION

A general trend is that fuel price is increasing while PV panel price is decreasing. Therefore, we calculated also the payback time to have a look into the future. The HFO fuel price is increased with 100 % being 1000 €/ton, since it has increased with 400 % during the last 12 years, and the PV investment cost decreased with 100 % to 1250 €/kW. The cost for wind power in this calculation was remained the same, 1500 €/kW. As can be seen in Figure 35 the payback time curve is not so fluctuating as it is with the current price level. Also, the payback time for 10 MW solar and 30 MW wind is reduced from 7.2 years to 3 years, which is as a significant change. This situation is highly possible in the future, and if it takes place, investing in renewable power generation in sun-belt countries with good weather condition is highly recommended. Payback time calculations for Figure 35 are done with solar radiation and wind speed at 100 % of the peak, where the average wind speed is 7.6 m/s and the average solar radiation 6 kWh/m^2/day.

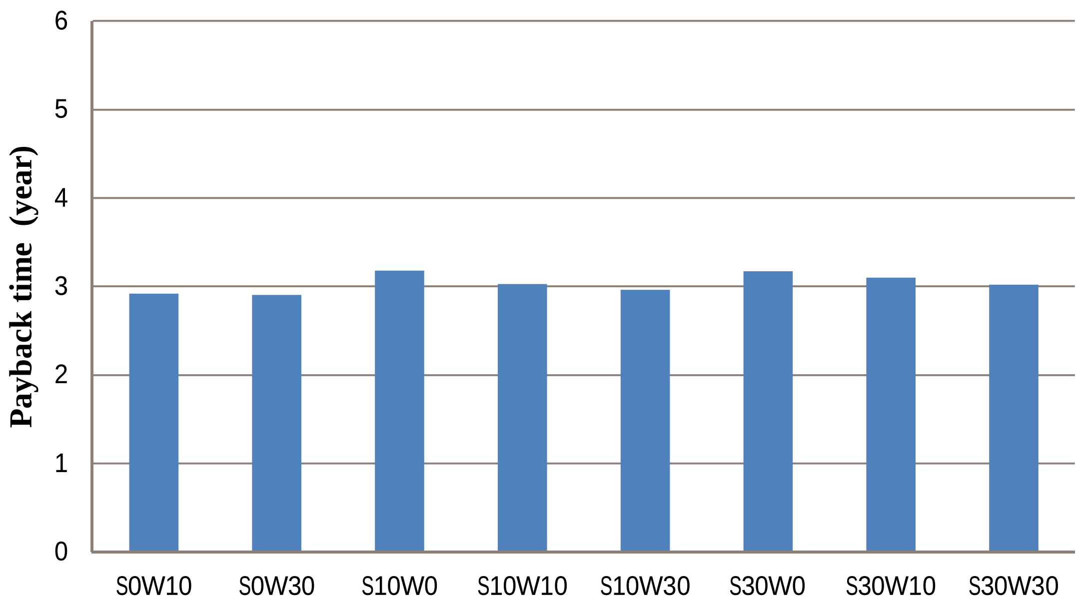

Figure 35. Payback time for different fluctuating load scenarios in the future, with both wind speed and solar radiation at 100 %. On Y-axis is the payback time in years and on X-axis are the different scenarios with different renewable penetration presented.

Subsidies aimed at reducing emissions can take on different forms, ranging from support for research and development, investment tax credits and price support mechanisms, such as the feed-in tariffs (Wilke 2011; 7). As mentioned earlier the FITs and other government subsidies were not taken into account in the calculations, due to a range of different and continuously changing subsidies depending on the country. Therefore, it should be taken into account when comparing payback times, since with the current investment costs the subsidies are pivotal for investment in renewable power generation.

When grid-parity, that moment when renewables produce electricity at same price as purchased from the grid, is reached the renewable market might grow very fast in case of low technical and legal obstacles (Breyer, Görig and Schmid 2011). However, also subsidies will be cut off at that same moment.

Due to possible locations on islands, high fuel and transportation costs, and also possible problems with regular fuel transport or space for larger storage tanks will most likely altogether affect positively the interest of investing in renewable power generation.

Hurtado, Gostales, de Lara, Moreno, Carrasco, Galván, Sancez and Franquelo (2002: 3326) stated already 10 years ago that hybrid power plants were “highly cost-effective”. Consequently, hybrid power plants should be extremely cost-effective today. Therefore, the problem does not lie in the economical profitability of renewable power generation, but rather in the short list of reference projects and lack of marketing of hybrid concepts.

The optimal hybrid concept is hard to define, despite numerous completed projects; the optimal hybrid concept is still case-specific. Nevertheless, studies of hybrid concept feasibility draw general lines in what is a must when designing a reliable and profitable hybrid power plant. With this knowledge the hybrid power plant should reach a relatively high efficiency and low payback time, if properly constructed.

For Wärtsilä the market situation for hybrid power plants is not either the best at the moment. Customers may have already enough power generation to meet the power demand and the payback time of 6 - 8 years is with this kind of huge investment still too long for developing countries. Nevertheless, a lot of the existing power generation is old and in need of being replaced or upgraded. Also, the power demand is increasing and hence, investment in hybrid power plants utilizing renewable energy instead of conventional power generation could be an option, due to minimization of fuel costs and emissions.

The minimization of own consumption is hard to estimate exactly by making calculations. Therefore, it could be studied further by making a pilot project at a site. Also, the minimization with a CSP system is only an option in the sunny locations. Hereby, a study of minimization of own consumption with the use of other systems could be worthy for Wärtsilä.

8 SUMMARY

The aim of this thesis was to calculate and design the ideal share of renewable energy in a hybrid power plant combined with Wärtsilä combustion engines for off-grid or small grid (10 - 300 MW) solutions. Also, minimization of the power plant's own consumption, especially pre-heating of the engines and fuel tanks with renewable energy was calculated.

First, the Wärtsilä power plant set-up was reviewed. The different combustion engines and their performances, starting and running, power plant automation and the different operating modes of the power plant were presented. Thereafter, a look of the challenges with power generation on islands and the affection of power quality when using renewable power generation were done. When there are long distances between the mainland grid and islands, savings could be made by adding power generation directly on the island, instead of installing a costly interconnection cable. Of power quality affections, voltage issues, such as fluctuation and dips, are considered mostly harmful when connecting renewable energy sources to the grid. Also, harmonic and frequency variations occur.

When constructing a hybrid power plant with renewable energy sources, not only the site and appropriate power generating systems are important, but also the management of generating sets and power quality, as well as the weather forecasting. Due to fluctuations in power generation with renewable energy sources, the fast starting combustion engines fit brilliantly together in a hybrid power generation concept with wind and solar power generating systems. Furthermore, adding of storage system was discussed and it would additionally increase the reliability of the power supply. On the other hand, the high cost and short lifetime makes it still a non-profitable solution that could be stepwise implemented to the power plant in the future when its technology has improved. Moreover, with the fast starting and load following combustion engine the stored fuel will work as storage system, responding to the power demand very fast.

The suitable combustion engines for a hybrid power generation concept at this size were also studied and due to the small size of the power plant (less than 100 MW) the optimal engine would be the 20V32 liquid fuel engine, the 20V34SG gas engine or the 20V32DF dual fuel engine, capable of using both liquid and gaseous fuels. These engines generate a maximum power of around 9 to 10 MW. The bigger combustion engines are not as suitable, due to their high power generation, which leads to less units in a power plant and thus the power supply is affected more during a possible trip of an engine. Besides, the smaller combustion engines are easier to transport and install at a site, which is especially considerable if the power plant is constructed on an island.

The minimization of own consumption, especially the pre-heating of the engines and fuel tanks, in existing Wärtsilä power plants with a concentrated solar power (CSP) system and thermal storage was reviewed. The CSP system fits in this concept well due to the efficiency of not converting the hot water to electricity, but utilizing it directly in the pre-heating, which is the biggest energy consumer in a stand-by power plant. Some calculations of the power plants' energy consumption and the payback time of the CSP system showed that if the power plant is located in a sunny area and is in pre-heated stand-by mode approximately 2/3 of the time during a year, the profitability would be great and the payback time is only 8.5 years.

In the economical view, renewable power generation systems, such as wind turbines and PV arrays are cost-effective nowadays. In this thesis some payback time calculations of hybrid power generation concepts were done, with the focus of savings in fuel costs when adding an amount of 10 - 40 % renewable penetration to a Wärtsilä power plant, using HFO as fuel. The simulations were made for two different kinds of power plants. One with a fluctuating load, which simulates a normal power demand on an island, and another one with a steady base load, mostly for power plants on industrial sites. The simulation results showed that a payback time of 5.8 years at lowest and an average of 8 years was possible to reach with the adding of solar and wind power if the weather conditions at site are suitable. The interest rate was not taken into account when calculating the payback time. However, with increasing fuel costs and decreasing electrical component costs, such as PV panels, the investing in renewables in near future is highly recommended. Especially on islands the fuel shipping and storing generates higher costs and possible issues. Therefore, a lot of possible customers for this hybrid concept are located on islands in the sun-belt countries with good weather conditions.

In this thesis the solar, wind and load data were simulated to fit each possible location separately. Due to this, all possible hybrid concepts have to be thoroughly planned and structured for all the different locations. Feed-in tariffs (FIT) and other subsidies were not taken into account in the calculations, and with their impact the payback times and thus the profitability of investing in a hybrid power plant would increase additionally.

The marketing of the profitability of these hybrid power generation concepts is a necessity, because in the end, it is always the attractiveness of the product from the customer's point of view that is the key to successful business.

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APPENDICES

Appendix 1. Wind speed data for one week in Aruba.

					100%	70%
Month	Day	Hour	m/s	Output, %	Wind profile	Wind profile
1	1	1	7,7	28	0,3	0,2
1	1	2	7,7	28	0,3	0,2
1	1	3	7,2	28	0,3	0,2
1	1	4	7,2	28	0,3	0,2
1	1	5	7,7	28	0,3	0,2
1	1	6	7,2	28	0,3	0,2
1	1	7	7,2	28	0,3	0,2
1	1	8	5,7	13	0,1	0,1
1	1	9	5,1	13	0,1	0,1
1	1	10	4,6	5	0,1	0,0
1	1	11	4,6	5	0,1	0,0
1	1	12	5,7	13	0,1	0,1
1	1	13	5,7	13	0,1	0,1
1	1	14	5,7	13	0,1	0,1
1	1	15	5,7	13	0,1	0,1
1	1	16	9,8	43	0,4	0,3
1	1	17	9,8	43	0,4	0,3
1	1	18	10,3	50	0,5	0,4
1	1	19	9,3	43	0,4	0,3
1	1	20	9,3	43	0,4	0,3
1	1	21	10,8	50	0,5	0,4
1	1	22	9,3	43	0,4	0,3
1	1	23	7,2	28	0,3	0,2
1	1	24	6,7	20	0,2	0,1
1	2	1	6,7	20	0,2	0,1
1	2	2	6,2	20	0,2	0,1
1	2	3	7,2	28	0,3	0,2
1	2	4	7,7	28	0,3	0,2
1	2	5	5,7	13	0,1	0,1
1	2	6	5,7	13	0,1	0,1
1	2	7	7,2	28	0,3	0,2
1	2	8	6,2	20	0,2	0,1
1	2	9	5,1	13	0,1	0,1

1	2	10	5,7	13	0,1	0,1
1	2	11	6,2	20	0,2	0,1
1	2	12	6,2	20	0,2	0,1
1	2	13	6,2	20	0,2	0,1
1	2	14	8,2	35	0,4	0,2
1	2	15	9,3	43	0,4	0,3
1	2	16	8,7	35	0,4	0,2
1	2	17	9,3	43	0,4	0,3
1	2	18	8,7	35	0,4	0,2
1	2	19	9,8	43	0,4	0,3
1	2	20	7,7	28	0,3	0,2
1	2	21	7,7	28	0,3	0,2
1	2	22	7,2	28	0,3	0,2
1	2	23	5,7	13	0,1	0,1
1	2	24	5,7	13	0,1	0,1
1	3	1	6,7	20	0,2	0,1
1	3	2	7,7	28	0,3	0,2
1	3	3	7,7	28	0,3	0,2
1	3	4	7,2	28	0,3	0,2
1	3	5	6,7	20	0,2	0,1
1	3	6	6,7	20	0,2	0,1
1	3	7	7,7	28	0,3	0,2
1	3	8	8,2	35	0,4	0,2
1	3	9	6,7	20	0,2	0,1
1	3	10	7,2	28	0,3	0,2
1	3	11	8,2	35	0,4	0,2
1	3	12	7,2	28	0,3	0,2
1	3	13	7,7	28	0,3	0,2
1	3	14	9,8	43	0,4	0,3
1	3	15	10,3	50	0,5	0,4
1	3	16	9,8	43	0,4	0,3
1	3	17	10,3	50	0,5	0,4
1	3	18	10,8	50	0,5	0,4
1	3	19	10,3	50	0,5	0,4
1	3	20	9,8	43	0,4	0,3
1	3	21	10,8	50	0,5	0,4
1	3	22	10,3	50	0,5	0,4
1	3	23	8,7	35	0,4	0,2
1	3	24	9,8	43	0,4	0,3
1	4	1	5,1	13	0,1	0,1
1	4	2	4,6	5	0,1	0,0
1	4	3	5,1	13	0,1	0,1

1	4	4	5,1	13	0,1	0,1
1	4	5	3,6	0	0,0	0,0
1	4	6	3,6	0	0,0	0,0
1	4	7	5,1	13	0,1	0,1
1	4	8	4,6	5	0,1	0,0
1	4	9	3,6	0	0,0	0,0
1	4	10	2,1	0	0,0	0,0
1	4	11	2,1	0	0,0	0,0
1	4	12	1,5	0	0,0	0,0
1	4	13	2,1	0	0,0	0,0
1	4	14	5,7	13	0,1	0,1
1	4	15	5,7	13	0,1	0,1
1	4	16	6,2	20	0,2	0,1
1	4	17	5,7	13	0,1	0,1
1	4	18	5,1	13	0,1	0,1
1	4	19	0	0	0,0	0,0
1	4	20	6,2	20	0,2	0,1
1	4	21	5,7	13	0,1	0,1
1	4	22	5,7	13	0,1	0,1
1	4	23	5,7	13	0,1	0,1
1	4	24	5,1	13	0,1	0,1
1	5	1	9,8	43	0,4	0,3
1	5	2	10,3	50	0,5	0,4
1	5	3	10,3	50	0,5	0,4
1	5	4	9,8	43	0,4	0,3
1	5	5	9,3	43	0,4	0,3
1	5	6	10,3	50	0,5	0,4
1	5	7	9,3	43	0,4	0,3
1	5	8	7,7	28	0,3	0,2
1	5	9	5,1	13	0,1	0,1
1	5	10	7,2	28	0,3	0,2
1	5	11	7,2	28	0,3	0,2
1	5	12	8,2	35	0,4	0,2
1	5	13	8,7	35	0,4	0,2
1	5	14	9,8	43	0,4	0,3
1	5	15	10,3	50	0,5	0,4
1	5	16	9,8	43	0,4	0,3
1	5	17	9,3	43	0,4	0,3
1	5	18	11,3	60	0,6	0,4
1	5	19	10,8	50	0,5	0,4
1	5	20	11,3	60	0,6	0,4
1	5	21	11,3	60	0,6	0,4

1	5	22	12,9	70	0,7	0,5
1	5	23	11,3	60	0,6	0,4
1	5	24	12,3	70	0,7	0,5
1	6	1	6,2	20	0,2	0,1
1	6	2	6,2	20	0,2	0,1
1	6	3	6,7	20	0,2	0,1
1	6	4	5,1	13	0,1	0,1
1	6	5	6,7	20	0,2	0,1
1	6	6	6,2	20	0,2	0,1
1	6	7	5,7	13	0,1	0,1
1	6	8	5,1	13	0,1	0,1
1	6	9	6,2	20	0,2	0,1
1	6	10	6,7	20	0,2	0,1
1	6	11	6,2	20	0,2	0,1
1	6	12	5,1	13	0,1	0,1
1	6	13	7,2	28	0,3	0,2
1	6	14	7,7	28	0,3	0,2
1	6	15	8,2	35	0,4	0,2
1	6	16	8,7	35	0,4	0,2
1	6	17	8,7	35	0,4	0,2
1	6	18	8,2	35	0,4	0,2
1	6	19	8,2	35	0,4	0,2
1	6	20	8,7	35	0,4	0,2
1	6	21	9,3	43	0,4	0,3
1	6	22	9,3	43	0,4	0,3
1	6	23	7,7	28	0,3	0,2
1	6	24	7,7	28	0,3	0,2
1	7	1	6,2	20	0,2	0,1
1	7	2	6,7	20	0,2	0,1
1	7	3	6,7	20	0,2	0,1
1	7	4	6,2	20	0,2	0,1
1	7	5	6,7	20	0,2	0,1
1	7	6	5,1	13	0,1	0,1
1	7	7	7,2	28	0,3	0,2
1	7	8	5,7	13	0,1	0,1
1	7	9	6,7	20	0,2	0,1
1	7	10	6,2	20	0,2	0,1
1	7	11	4,6	5	0,1	0,0
1	7	12	5,1	13	0,1	0,1
1	7	13	4,6	5	0,1	0,0
1	7	14	7,2	28	0,3	0,2
1	7	15	7,2	28	0,3	0,2

1	7	16	8,7	35	0,4	0,2
1	7	17	7,7	28	0,3	0,2
1	7	18	7,7	28	0,3	0,2
1	7	19	8,2	35	0,4	0,2
1	7	20	8,2	35	0,4	0,2
1	7	21	7,7	28	0,3	0,2
1	7	22	7,7	28	0,3	0,2
1	7	23	6,7	20	0,2	0,1
1	7	24	6,7	20	0,2	0,1

Appendix 2. Monthly average solar power generation data in MW with 15 min intervals.

15 min	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	1	0	0	0	0	0	0
16	0	0	0	0	0	7	3	0	0	0	0	0
17	0	0	0	0	3	21	14	0	0	0	0	0
18	0	0	0	1	18	47	37	3	0	0	0	0
19	0	0	0	1	64	112	88	11	0	0	0	0
20	0	0	0	3	130	215	170	22	0	0	0	0
21	0	0	0	25	293	396	319	81	2	0	0	0
22	0	0	3	108	495	594	513	199	12	0	0	0
23	0	0	5	270	725	878	764	365	35	0	0	0
24	0	0	9	486	1 099	1 194	1 020	576	112	0	0	0
25	0	0	45	813	1 565	1 648	1 399	923	296	10	2	0
26	0	0	161	1 204	2 119	2 119	1 939	1 381	602	68	8	1
27	0	0	359	1 734	2 725	2 703	2 576	1 923	981	251	34	1
28	0	0	682	2 290	3 388	3 385	3 140	2 522	1 479	525	81	2
29	0	12	1 141	2 918	4 142	4 134	3 822	3 211	2 173	1 039	229	21
30	0	138	1 708	3 641	4 887	4 887	4 553	3 953	2 879	1 655	389	48
31	0	371	2 334	4 373	5 672	5 623	5 287	4 727	3 659	2 359	577	126
32	0	628	2 983	5 046	6 379	6 405	5 967	5 457	4 507	3 094	919	234
33	63	1 203	3 586	5 878	7 101	7 118	6 666	6 205	5 364	4 029	1 225	369
34	165	1 817	4 476	6 784	7 796	7 824	7 432	6 906	6 285	4 925	1 748	629
35	295	2 473	5 396	7 403	8 501	8 506	8 024	7 612	7 059	5 868	2 236	904
36	451	3 190	6 319	8 107	9 103	9 072	8 691	8 289	7 927	6 763	2 868	1 218
37	899	4 064	7 177	8 770	9 744	9 655	9 343	8 893	8 646	7 579	3 504	1 571
38	1 350	4 934	8 032	9 384	10 373	10 194	9 948	9 378	9 324	8 358	4 165	1 883
39	1 855	5 772	8 791	10 028	10 899	10 598	10 376	10 081	9 832	9 046	4 766	2 194
40	2 354	6 547	9 480	10 578	11 420	11 028	11 012	10 538	10 258	9 653	5 294	2 584
41	3 027	7 240	10 085	11 095	11 795	11 430	11 250	11 047	10 667	10 233	5 830	3 048
42	3 746	7 778	10 441	11 396	12 144	11 832	11 722	11 400	11 109	10 789	6 178	3 478
43	4 359	8 346	10 966	11 738	12 451	12 113	11 843	11 836	11 463	11 250	6 664	3 878
44	4 851	8 783	11 200	12 076	12 686	12 314	12 206	12 001	11 757	11 638	7 036	4 091
45	5 250	9 151	11 458	12 326	12 901	12 523	12 416	12 282	12 096	12 008	7 401	4 230
46	5 564	9 430	11 739	12 506	13 111	12 674	12 557	12 354	12 147	12 257	7 623	4 310
47	5 740	9 621	11 885	12 535	13 085	12 751	12 607	12 549	12 296	12 514	7 802	4 372
48	5 917	9 752	11 834	12 625	13 160	12 816	12 767	12 292	12 388	12 582	7 958	4 336
49	5 972	9 852	11 992	12 686	13 070	12 877	12 675	12 742	12 452	12 484	7 926	4 254
50	6 043	9 885	11 988	12 760	13 177	12 954	12 689	12 652	12 448	12 427	7 878	4 142
51	5 991	9 836	12 037	12 747	13 104	12 887	12 714	12 621	12 372	12 327	7 723	4 132
52	6 060	9 707	11 917	12 559	12 978	12 814	12 487	12 633	12 175	12 055	7 402	3 765
53	5 928	9 524	11 812	12 449	12 679	12 580	12 161	12 452	11 958	11 794	7 056	3 609
54	5 907	9 275	11 685	12 291	12 474	12 421	12 008	12 091	11 602	11 435	6 556	3 407
55	5 742	9 043	11 506	12 086	12 240	12 228	11 728	11 843	11 391	11 033	6 100	3 284
56	5 502	8 683	11 126	11 616	11 952	11 963	11 379	11 737	11 117	10 570	5 598	2 891
57	5 143	8 135	10 854	11 293	11 670	11 719	10 926	11 392	10 740	10 098	4 977	2 480

58	4 893	7 826	10 464	10 718	11 303	11 288	10 647	11 037	10 266	9 584	4 364	2 223
59	4 530	7 153	9 917	10 152	10 934	10 831	10 216	10 561	9 729	8 982	3 712	1 914
60	4 083	6 620	9 346	9 687	10 478	10 426	9 633	9 977	9 286	8 357	3 101	1 597
61	3 565	6 059	8 726	9 032	10 009	9 982	9 310	9 537	8 721	7 681	2 508	1 239
62	3 109	5 375	7 973	8 426	9 465	9 521	8 783	8 921	8 065	6 902	1 966	903
63	2 455	4 721	7 273	7 847	8 928	8 937	8 273	8 334	7 453	6 091	1 532	574
64	1 901	3 958	6 504	7 120	8 349	8 378	7 571	7 634	6 828	5 286	1 092	345
65	1 413	3 297	5 833	6 359	7 650	7 780	7 067	7 233	6 144	4 443	770	252
66	896	2 573	4 916	5 563	6 917	7 139	6 806	6 619	5 307	3 564	499	285
67	496	1 864	4 285	4 809	6 185	6 354	6 018	5 947	4 574	2 698	286	285
68	199	1 280	3 609	4 104	5 466	5 628	5 527	5 279	3 830	1 884	217	285
69	49	775	2 774	3 359	4 698	4 903	4 598	4 607	3 073	1 216	217	285
70	20	373	2 135	2 733	4 017	4 198	4 061	3 871	2 424	672	0	43
71	5	135	1 510	2 073	3 267	3 550	3 392	3 110	1 897	292	33	0
72	0	38	1 008	1 591	2 678	2 925	2 816	2 504	1 404	187	0	0
73	0	14	516	1 145	2 044	2 375	2 276	2 002	954	187	0	0
74	0	1	204	772	1 560	1 911	1 818	1 575	595	0	0	0
75	0	0	49	496	1 170	1 516	1 376	1 146	321	0	0	0
76	0	0	12	261	813	1 092	1 069	794	136	14	0	0
77	0	0	0	119	554	783	772	534	54	0	0	0
78	0	0	0	46	352	546	563	340	0	0	0	0
79	0	0	0	14	186	351	374	152	0	0	2	0
80	0	0	0	0	84	200	220	59	0	0	1	0
81	0	0	0	0	30	89	102	23	0	0	0	0
82	0	0	0	0	10	36	45	0	0	0	0	0
83	0	0	0	0	0	13	16	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0
94	0	0	0	0	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0	0	0	0	0	0	0
96	0	0	0	0	0	0	0	0	0	0	0	0