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5MWP PV + BESS FEASIBILITY

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Tämän opinnäytetyön tavoitteena on tutkia sähkökemiallisen energiavaraston kannattavuutta aurinkosähkövoimalan ohessa, sekä tutkia suomalaisia reservimarkkinoita ja akkuvaraston hyödyntämistä näillä markkinoilla.

Tutkimuksessa käytettiin bisnestapaustutkimusmenetelmää. Tiedot kerättiin lukemalla tutkimusartikkeleita ja keräämällä tietoja yhteistyöyrityksiltä.

Tutkimuksen tulos osoittaa, että PV pelkästään on kannattavampaa kuin PV + BESS ainakin silloin, kun akkuvarastoa käytetään energian arbitraasiin.

Avainsanat	Energiavarasto, uusiutuva energia

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ABSTRACT

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The aims of this thesis were to investigate the profitability of electrochemical energy storage alongside solar a PV system, as well as to investigate the Finnish reserve market and the utilization of the battery storage in this market.

The research used a business case as the research method. The information was collected by reading research articles and collecting information from cooperating companies.

The result of the research shows that standalone PV is more profitable than compared to PV + BESS, at least when the BESS is used for energy arbitrage alone.

Keywords Energy storage, renewable energy

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1 INTRODUCTION

1.1 Background

The global climate crisis is becoming more alarming in our everyday life. Part of the cause for this is the large quantities of CO2 that are released into the atmosphere every day. The greenhouse gases are causing a large problem with the raising global average temperature which will be at least 1,2˚ in 2023 compared to pre-industrial average. /1/ This is causing increasing amounts of natural disasters around the globe. A large part of these CO2 emissions is created from energy production with fossil fuels for example, incineration and combustion powerplants. In the future our energy will need to be made by using renewable energy as much as possible. This fuels our development of making our renewable energy powerplants as clean and efficient as possible.

This thesis was done for Etha Wind Oy as they are looking into the feasibility of battery energy storage systems and solar power plants in the Finnish market. Etha Wind Oy is a project development consulting company that specializes in renewable energy mostly in wind and solar projects. They have played and continue to play a big part of the Finnish wind power development for 21 years now.

1.2 The Research Problem

Solar photovoltaic powerplants are still relatively uncommon in Finland due to the long and dark winter season when solar panels do not produce energy as much as wind power for example, but they are coming to the markets fast. In the future when there will be more and more renewable energy, more short- and long-term energy storage systems will be needed to store the energy produced when it is possible and use it when the production of energy is not possible for example in the night when solar panels are not producing.

Self-sufficient energy production nowadays a controversial topic since Russia has stopped providing its energy to Europe. Effected countries are trying now more than ever to produce their own energy so that they are dependent on other countries production, which might leave them without energy for some time.

The solar photovoltaic system can help Finland to go towards self-sufficiency, eco-friendly energy and the energy storage will make a renewable energy power plant more flexible, because we can make the energy available even when the sun is down and there is no energy production from the PV system. The battery storage system will also help balance the grid by detecting the frequency change and reacting to it in seconds, preventing grid failure.

The knowledge of the energy reserve market in Finland will become important when planning for a energy storage project. Knowing the reserve market profits will be critical in our calculations of the profitability of the hybrid system. Being a part of the reserve market will be a large part of all energy storage options in the future, especially battery storage because of its fast response time it can be used as an FCR to help balance the grid. /12/

1.3 Research Objectives

Based on the problems named above this thesis aims to answer these questions:

1. Will the BESS be profitable when attached to 5MWp solar PV system?
2. How does the reserve market work in Finland?

1.4 Methods and Scope

The objective of this thesis is to find out if the battery energy storage is feasible. The production calculations for the solar PV will be made by using the PVsyst software. Since there is not enough data from these kind of hybrid systems in Finland, the research is based mostly on the data PVsyst gives us. The scope of the study is to understand the benefits of the hybrid system and to understand the energy

market more, so that it is possible calculate accurately the economic benefit of the storage. This research was done for a site which is located in northern Ostrobothnia, Raahe but it can be implemented around Finland by changing couple of parameters in the production calculations.

2 DEVELOPING A SOLAR PV POWER PLANT

There are three types of solar energy technology. One of them is called solar heating where the concentrated sunlight is used to heat up water, which can then be used in various applications. Another technology called concentrated solar power, uses concentrated solar irradiance directly to generate steam, which is then injected into a steam turbine to convert mechanical energy into electrical energy. The technology that we are focusing on in this thesis is solar photovoltaic that refers to a technology that converts sunlight directly into electricity.

2.1 Factors Impacting the Production of Solar PV

There are many different factors that will affect the overall energy production of a solar PV system (see Figure 1.). Reaching as high as possible specific production per panel is critical for the project to be profitable. Generally, the selected place should have adequate exposure to an optimum amount of sunlight, be free from shading, have lesser sources of pollution and have a suitable soil type. /2/

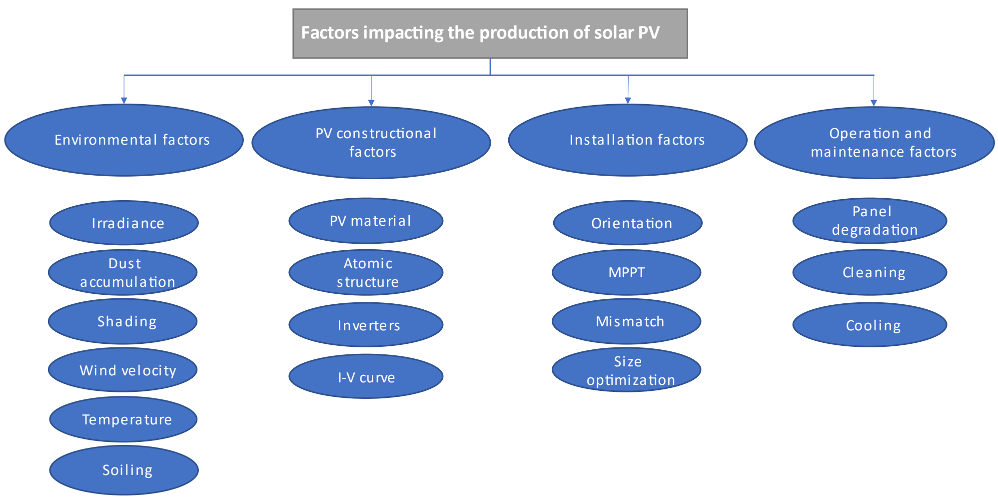

Figure 1. Factors impacting the production of solar PV. /5/

2.1.1 Solar Irradiance

Irradiance is the energy that strikes a unit horizontal area per unit wavelength interval per unit time. The PV panel output depends significantly on solar power or solar irradiance with the solar resource being highly variable. Irradiance varies due to weather, geographical location, the suns position in the sky, seasonal changes and time of the day. Cloudy weather and rain are most responsible for the variability in the irradiance value. The PV modules receive both direct and scattered radiation from the sky, nearby objects and ground. A significant part of the radiation is the direct solar radiation. The effect of the irradiance on the performance of the PV panel cannot be computed by a particular percentage due to the linear relationship between the module current and irradiance value. /5/

2.1.2 Temperature

The effective generation of electricity from a photovoltaic panel is closely linked to its module temperature. As the temperature of the PV panel rises, the efficiency of its electrical conversion decreases. This is because PV panels can only convert approximately 20% of the solar energy they receive into electricity, with the remaining 80% being converted into heat. The module temperature is a function of environmental factors such as wind speed, solar irradiance, ambient temperature and PV constructional factors such as materials and glass transmittance. The module temperature can be calculated using the following formula:

$$T_{mod} = T_{amb} + Irradiance * \exp(-a - b * WS) + \Delta T * \frac{Irradiance}{1000}$$

Where a, b and ΔT are the constants and for glass/cell/polymer sheet the values are 3.56, 0.0750 and 3. /5/ The best temperature for the module is as low as possible. This is why we get relatively high production levels during spring in Finland, when the irradiation is high, but the air temperature is low.

2.1.3 Dust Accumulation

The efficiency of the PV modules is varied due to dust, air molecules, water vapors and other pollutants in the atmosphere. These can obstruct sunlight from reaching the panels, resulting in reduced efficiency. Dust can also form a thick layer on the PV modules surface. A dust layer can change the optical properties to promote light reflection, absorption and reduce surface transmissibility, therefore reducing the PV module output. Dust accumulation is determined by environmental factors, such as humidity, rainfall, source of dust particles, wind velocity, particle type, PV module technology and PV module surface cover. The most severe problems are at desert areas with low rainfall. /5/

Dust particles are able to settle on the module cover due to gravitation; these particles then absorb water vapor from the humidity and form adhesive and sticky residue on the panel surface. The rainfall plays a large part in the cleaning of the PV panels, and it also reduces the dust density in the air, but the panels should still be cleaned on an appropriate cleaning cycle to be able to maximize production /5/. In our case the PV panels will not be cleaned on a regular basis, because of the low amount of dust, the high panel table tilt angle and the good amount of rainfall in our location.

2.1.4 Soiling

As mentioned in the previous chapter, the dust particles land on the PV panel surfaces and absorb water from air to develop residue. The atmospheric humidity highly influences the adhesive force between dust particles and the PV panels surface, therefore an increase in humidity increases dust accumulation. Soiling on the surface of the PV panel results in hard and soft shading, this ultimately leads to a decrease in power output. Smog in the atmosphere is responsible for soft shading, and soil mass or residue on the panel causes the hard shading. The impact of dust and other particles on PV power generation varies depending on the location, as they can affect light transmission differently.

The effect of the soiling can be greatly decreased by raising the panel tilt angle. /5/ In our case the soiling should not be an issue because of the low dust settling on the panels with a high tilt angle.

2.1.5 Wind Velocity

Wind speed plays a large factor in the performance of the solar PV panels, as research done by University of Malaysia Perlis shows. The research they have done shows an increase in energy production of 14,25% when a single panel is getting hit with wind versus a single panel that is not getting hit by wind. This is caused by lowered panel temperature which increases power production and improves the longevity of the PV panel /3/. Wind speed has a greater influence on the temperature of PV cells than wind direction. The design and structure of the PV panel surface play a significant role in its cooling. While grooved and structured glass covers may provide effective cooling in high wind speed conditions, they may not perform well in low wind speed scenarios compared to a flat surface. /5/

Wind also has a profound effect on dust deposition on the PV panel surface, unless if the surrounding area consists of sand which might be flown around by wind and deposed on the panels. /5/

2.1.6 Shading

Shading occurs when an object or structure fully or partially blocks the sunlight from reaching the PV panel, leading to a reduction in the amount of energy generated. The shadowing effect lowers the PV power output. There are various types of shadings, such as soft shading, near-shading and hard shading. Soft shading is atmospheric dust, fog and smoke that reduces the irradiance intensity. Near-shedding is caused by the panel row in front of the panel. Hard shading occurs due to the accumulation of dust, bird droppings, snow or leaves. Additionally, poles, trees and buildings block the sunlight in a clear and definable shape. The horizon has a large effect on the shadings because a mountain can provide a very large shade.

This is why solar PV plants are preferably built on sites with as flat horizon as possible. /5/

The reduction in output of PV modules is largely determined by the position of the module, configuration of the array, and the extent of shading, whether it is partial or complete. Partial shading blocks some cells of the PV module and severely affects module output due to the shaded cells not being able to produce any current. Partial shading causes the current produced by non-shaded cells to flow through the shaded cells negative voltage region and dissipates power rather than generates. /5/

2.1.7 Humidity

The amount of moisture in the air, or relative humidity, can have a significant impact on the efficiency of PV panels. This is because the atmosphere can cause small water droplets and water vapor to accumulate on the panels, which can scatter, reflect, or absorb sunlight and reduce energy output. Long-term exposure to humidity also corrodes the PV modules due to the moisture ingression to the solar cell. In addition, humidity does not do any good for the whole power station system. /5/

2.1.8 Degradation

The PV systems capability to generate power may be impacted by panel degradation, which is the progressive weakening of the systems characteristics over time. Several factors cause PV module degradation such as temperature, humidity, irradiation and mechanical shock. Solar PV panels usually degrade at a faster rate in the first few years of their life. In general, the degradation is at about 0,5% per year. A solar PV panel is degraded when its power reaches below 80% of its initial power. /5,6/

2.1.9 PV Module Orientation

The best PV module orientation for the northern atmosphere is to face true south and the panels should be tilted equal to geographical latitude of the site for the optimal energy production for fixed tilted plane. The tilt of the module can also be optimized for the summer and winter season by using the following formula. For summer tilt:

$tilt_{summer} = Latitude - 15^{\circ}$ /2/

During winter the tilt angle can be found by using formula:

$tilt_{winter} = Latitude + 15^{\circ}$ /2/

2.1.10 Grid Connection

The grid connection is also a very important point to take into consideration when planning a powerplant site. Closer the grid to the site is, the less new powerlines will need to be built. This makes the capex costs significantly lower. The grid connection agreement might prove to be difficult to get especially in the Western Ostrobothnia region because of the current grid limitations due to grid congestion.

2.2 Components of Hybrid Solar PV System

2.2.1 Solar Panels

To create energy from the sunlight, solar panel arrays are needed which consist of multiple solar panel strings connected in a parallel form. A string consists of multiple solar panel modules connected in series, which is formed of multiple solar cells connected in a series /2/. The panels in our case will be bifacial. Bifacial panels use a double-sided solar cell design that allows sunlight to be absorbed from the front and the back of the panel. A recent study focused on the optimization on the performance of the bifacial modules showed a 10% gain at 0.25 albedo in ground mounted modules /4/. In the reference project the albedo cannot be as high, but

still there is a 5,5% gain from the bifacial panels which is adequate to compensate for the increase in panel price.

2.2.2 Solar Tracking Systems

Since the sun moves from the east to the west daily and also differs in its position and path in the sky on a seasonal basis, the maximum solar energy can be captured from the PV module if it continuously faces towards the sun. This is why solar tracking systems were invented, to significantly raise the efficiency of the solar PV modules when compared to fixed mounting. /2/

There are two types of tracking systems. Single axis tracking can only rotate from east to west following the sun or only rotate the tilt angle, whereas dual axis tracker has the east-west and south-north tracking availability. The single axis tracking system will need fewer parts and therefore, will be cheaper, but the dual axis tracker will be more efficient. In the reference project there will not be any tracking systems, instead fixed mounting will be used.

2.2.3 Inverters

The DC electricity from the solar arrays is converted to AC electricity in the solar inverters. The AC electricity is then connected to a switchgear and a step-up transformer, which feeds the power to the grid. The energy storage system will have its own inverters.

2.2.4 Cabling

DC cabling is needed between the panel modules and inverter. AC cabling is used to connect the inverter to MV switchgear and from MV switchgear to step-up transformer. It is important to have the correct size of cables to ensure minimal electricity losses but not to oversize too much, which will be expensive and decrease the profits.

2.2.5 Battery Energy Storage

A large part of the hybrid system is the battery energy storage system, which makes the system more flexible by making the energy available when it cannot be produced by the PV plant. The four major categories of rechargeable batteries being used today are lead acid batteries, alkaline batteries, silver batteries and lithium batteries. /7/ In our case lithium battery storage used.

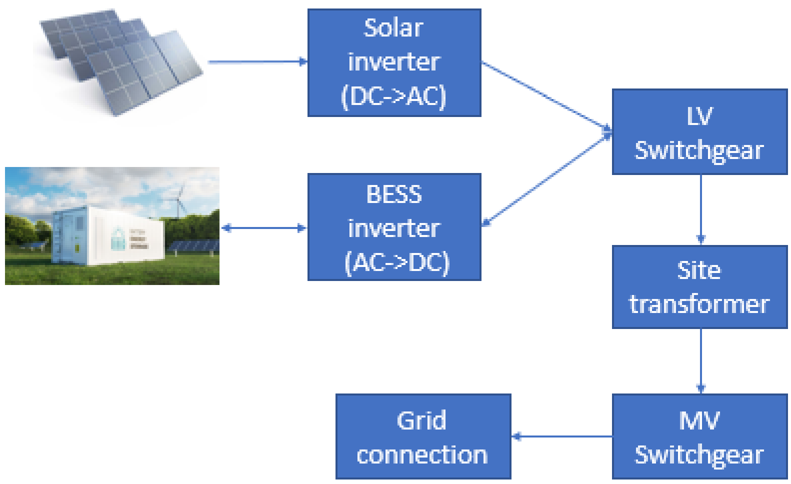

Figure 2. Main components of the Hybrid power plant

2.3 Output of the Solar Power Plant

The energy output of a solar power plant refers to the amount of electrical energy that is produced by the plant over a given time period (see Figure 3.). The output of the plant depends on several different factors which have been stated in section 2.1. To determinate the production of solar photovoltaic in the reference project PVsyst software was used for the calculations. PVsyst is widely used by PV system designers, engineers and installers to simulate and optimize the performance of PV systems. PVsyst states that the accuracy of the simulation is within 1-2% per year of simulation.

The electric energy calculation formula is:

$$E = P * t$$

Where E is energy transferred in kilowatt-hours, P is the power in kilowatts and the t is time in hours.

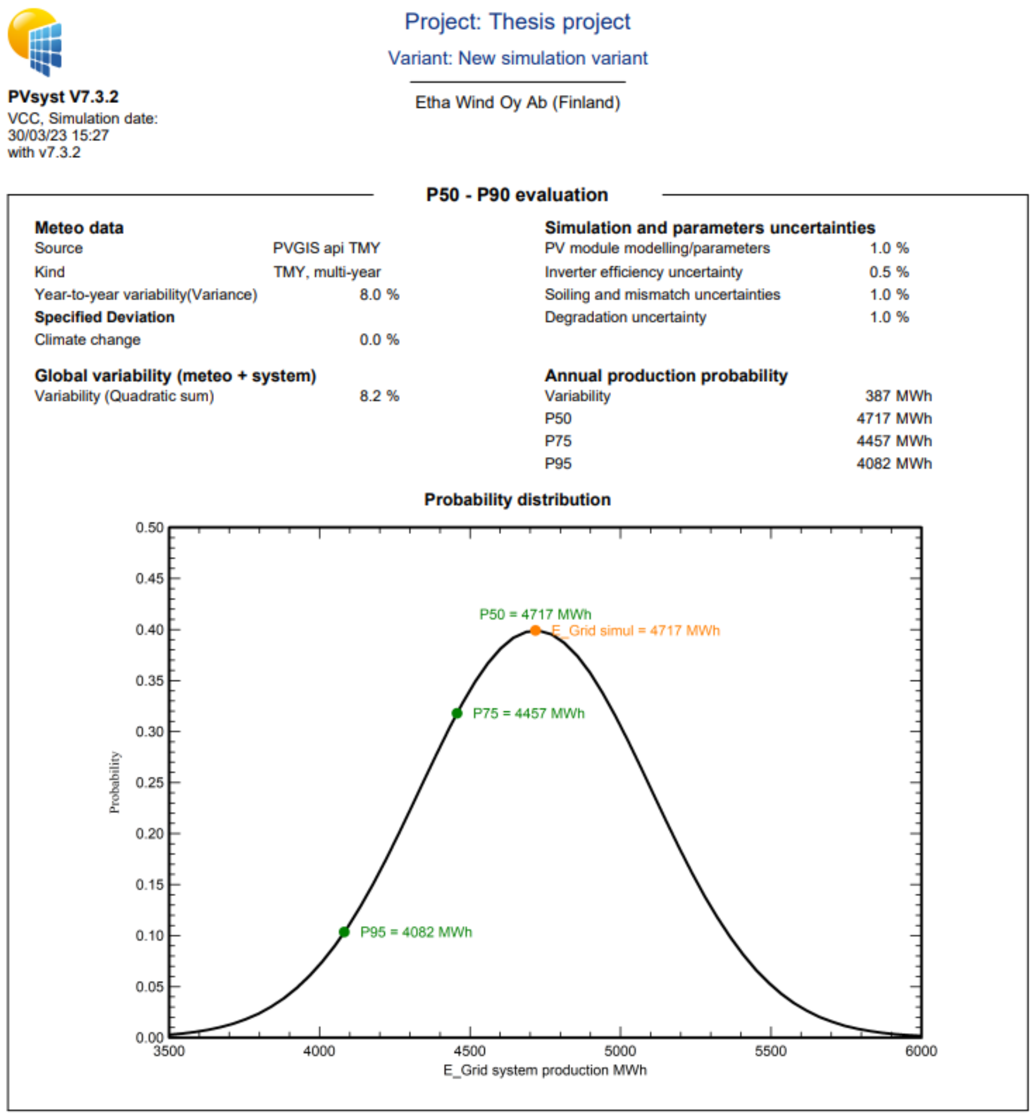

Figure 3. Solar photovoltaic yearly production curve from the PVsyst.

3 ENERGY STORAGE

Energy storage is the process of capturing energy and storing it for later use. Energy storage systems play an important role in the integration of renewable energy sources, such as solar and wind. ESS can help to address the intermittent nature of these energy sources by storing excess energy when it is available and releasing it when it is needed. There are three different types of energy storage including mechanical storage, electrical storage and electrochemical storage (See Figure 4).

Energy Systems		Storage	Specific Energy density (W h/kg)	Power rating (MW)	Other characteristics (advantages and disadvantages)	Applications
Mechanical storage		PHS	0.5–1.5 [39]	100- 5000 [39] 3000 [6]	High capacity, liable to environmental risks [6], seasonal storage, high capital cost [10].	Utility purpose [6], isolated or distributed networks [8, 9],
		CAES (large scale)	0.5–2 [39]	Up to 300 [11, 39]	Can only be used in large scale [5]. Relatively low round trip efficiency when compared to PHS [6].	Load shifting, frequency and voltage controlling grid applications [40-43].
		FESS	10-30 [39], 5-100 [5]	<0.25 [39], 0.1-20 [7]	High operational storage capital cost, difficult for bulk electricity storage [10]; Ineffective for energy backup in standalone power applications [6].	Stores rotational kinetic energy in rotating machinery or rotating flywheels [7, 11]
Electrical storage		Super-capacitors	2.5-15 [39]	0-0.05 [39]	High energy efficiency, long service life [7, 44]; Low specific energy [39]; High capital cost, about 5 times costlier than lead acid battery [6, 45].	Short term storage applications [6], applications requiring many charge-discharge cycles e.g, regenerative breaking [7].
		Super-conducting magnets	10–30 [39]	0-0.3 [6, 39]	Storage can persist continuously for years with no measurable resistance [6, 17]. Has a very high capital cost up to $10,000/kWh, uneconomical for utility scale systems [6, 7, 10].	Due to its fast discharge rate [7], SMES is more suitable for short term energy storage in energy and power system application [6].
Electrochemical storage	*Rechargeable battery*	Lead acid	30-50[22, 39]	0-20 [39] 0-40 [21]	Low cost, high reliability and high efficiency [21]; relatively bulky, cannot be left in the discharged state for long without damage [22, 25].	Photovoltaic applications [10, 46], automotive applications, emergency power supply system, uninterruptible power supplies (UPS) system, and traction for industrial truck [19, 20]
		NiCd	50-75 [22, 39], 0-40[39]	0-40 [39]	Mechanically rugged, long service life, excellent low temperature characteristics [20, 22, 23]; More expensive than lead acid batteries, have "Memory effect" [47-49].	Stand by and emergency power system such as in photovoltaic applications [25, 50].
		Li-ion	75-200 [39]	0-0.1 [39] 1-100 [6]	High Efficiency (over 95%), long life, high cycle of about 3000 at 80% depth of discharge, high energy density [39]; high cost (above $1200/kW h) and requires safety circuitry [21].	Renewable energy applications [6, 7], Hybrid and full Electric Vehicles (HEVs and EVs)[6]; Portable electronics such as laptop computers and power tools [51-53].
		NaS	150-240 [39]	<8 [39] <34 [21]	Promising for high power energy storage applications [7]. No self-discharge, high energy density, 85% energy efficiency [29]. Requires a high operating temperature about 350 ^{0}C [28].	Load leveling, wind & solar power applications, refueling of the fixed route vehicles [6, 54, 55]
	(Redox) Flow battery	VRB	10-30 [39]	166 [56]	Quick responses (faster than 0.001 s) and can operate for 10,000–16,000+ cycles [34, 57]. Up to 85% high efficiency [34, 58].	Suitable for small and medium scale applications [21]; Promising for load leveling and seasonal energy storage in stand-alone photovoltaic systems [59].
		ZBB	30-50 [39]	0.05-2 [39]	Deep discharge capability, Good reversibility, relatively high energy density [6, 39]. Prone to material corrosion and dendrite formation [60]; have relatively low cycle efficiencies compared to traditional batteries[60].	applications using ZBB are in the early stage of demonstration /commercialization [6]. Some trials are being conducted on ZBB for use in grid support and reliability applications [6].
		PSB	15-30 [6, 32]	1-15 [39]	No self-discharge [7], fast response characteristics, electrolytes material are abundant and cost-effective [6].	Long term energy storage applications [7], also being developed for power system frequency control and voltage regulation [6].

Figure 4. Basic comparison and characteristics of common energy storage systems. /7/

3.1 Mechanical Storage

The mechanical energy storage system converts the renewable energy into mechanical energy. It stores mechanical energy in the flywheel energy storage, compressed air energy storage or pumped hydro storage.

3.1.1 Pumped Hydro Storage

A pumped hydro storage is a large-scale energy storage system. Its operating principle depends on gravitational potential energy of water flow from a higher water reservoir to a lower vertically separated water reservoir. During times of low electricity demand or when renewable energy sources are available, water is pumped to an elevated reservoir. Then, when electricity demand increases, the water is released from the upper reservoir to the lower reservoir, driving turbines to generate electricity. PHS is a commonly used energy storage technology with a capacity to generate as much as 3000MW of electricity. /7/ However, there are a few drawbacks to this storage system, the installed capital cost is high compared to other types of storages. PHS is difficult to build in places with flat ground because of the elevation difference of the reservoirs will be hard to create.

3.1.2 Compressed Air Energy Storage

The compressed air energy storage stores energy in air by compressing it to a very high pressure. The excess energy supply from renewable sources or from the grid during a low power demand period is utilized to drive a reversible motor unit. This in turn powers a chain of compressors for injecting air into storage tanks. During the operation, the compressed air is heated at a constant pressure in the combustor and finally captured by a gas turbine to generate electricity. During the process, there is a byproduct of heat energy which can be recycled into the system using a recuperator for heating the compressed air. The limitation of this storage system includes a relatively low roundtrip efficiency especially when compared to battery technologies or PHS. /7/

3.1.3 Flywheel Energy Storage System

The flywheel energy storage system is designed to hold rotational kinetic energy in rotating machinery or flywheels. In this system, when the flywheel functions as a motor, it gains momentum and transfers its rotational energy into the storage device within the system /7/. The stored energy can be calculated by using the next formula:

$$E_c = \frac{1}{2} * I * w^2$$

Where I is the moment of inertia and w is the angular velocity /8/. The process of discharging the stored kinetic energy is through a regenerative deceleration of the system. The limitations of the system are ability to provide electricity only for a short period of time with a modest capacity. Moreover, the FESS is subject to losses resulting from significant self-discharge rates. These rates can amount to as much as 20% of the stored capacity per hour during idle periods when the flywheel is in standby mode. /7/

3.2 Electrical Storage

Electrical storage stores energy in electrical form in superconducting magnets or Supercapacitors. /7/

3.2.1 Supercapacitor Energy Storage System

A supercapacitor energy storage system stores energy using one or multiple supercapacitors, which are electrostatic double-layer capacitors with a high capacity. These capacitors have an energy density of 10-100 times more than electrolytic capacitors and can accept and deliver charges at a much faster rate than batteries. Additionally, they can handle more charge-discharge cycles. Supercapacitors are suitable for applications that need frequent charge-discharge cycles rather than long-term, compact energy storage. /7/ The limitations of this system are high capital cost and low specific energy.

3.2.2 Superconducting Magnet Storage System

When a material becomes superconducting, it allows electric current to flow without any resistance at temperatures below a specific critical point. This means that when electric current is passed through a loop of superconducting wire at this temperature, it can continue without requiring additional power. The concept behind a superconducting magnetic energy storage (SMES) system is to store electrical energy within a magnetic field. To generate electrical energy, a direct current is passed through a large coil made of superconducting materials, such as vanadium or mercury that have been cryogenically cooled below their critical temperatures. SMES has a significant advantage of almost zero energy losses, making its round-trip efficiency very high. It is a promising energy storage technology for applications that demand high power output and quick response times. However, it may not be suitable for applications requiring long-term energy storage because of its high cost and limited energy capacity. /7/

3.3 Electrochemical Energy Storage System

An electrochemical energy storage system is alternatively referred to as the Battery Energy Storage System since it utilizes rechargeable batteries to store energy. There are four primary types of rechargeable batteries implemented in various applications today: lead-acid batteries, alkaline batteries, silver batteries and lithium batteries. /7/

3.3.1 Lead Acid Batteries

The lead-acid battery was first discovered by Plante in 1860 and is presently one of the most extensively utilized rechargeable batteries. There are two common types of sealed lead-acid batteries, absorbent glass mat-valve regulated lead-acid and gel-valve regulated lead-acid. Apart from photovoltaic applications, lead-acid batteries are widely used in the automotive industry and various other sectors. The advantages of this energy storage system are its low cost, high voltage per

cell, good capacity life and excellent performance at room temperatures. However, its disadvantages include poor low-temperature characteristics and damage caused when left in the discharged state for an extended period and higher weight when compared to other battery types. /7/

3.3.2 Alkaline Secondary Batteries

Alkaline secondary batteries, also known as Nickel batteries, are a group of rechargeable batteries that rely on an aqueous solution of alkaline-based electrolytes, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), to function, as opposed to the acid electrolyte used in lead-acid batteries. The common alkaline battery technologies include Nickel-Cadmium (NiCd), Nickel-metal Hydride (NiMH), Nickel-Iron (NiFe) and Nickel-Zinc (NiZn). The advantages of alkaline batteries include their high continuous power provision capacity, fast recharge rate and long service life /7/. Disadvantages include a higher price than lead acid batteries and the environmental concerns for especially the Nickel-Cadmium batteries /9/.

3.3.3 Silver Batteries

Rechargeable silver-zinc batteries, also known as Zinc-silver oxide batteries, are composed of a metallic zinc anode and a silver oxide cathode immersed in an aqueous solution of potassium hydroxide electrolyte. Silver batteries primarily comprise silver-zinc and silver-cadmium batteries, whereas other types, such as silver-hydrogen and silver-metal hydride, have not yet attained commercial viability. The advantages of silver batteries include their high energy density and low self-discharge characteristics. However, the major disadvantage of silver batteries is their high cost. /7/

3.3.4 Lithium Batteries

Li-ion batteries exchange lithium ions (Li+) between the anode and cathode, which are made from lithium intercalation compounds. The cathode is usually made of

lithium metal oxide ($LiMEO_2$), with the anode of the made of graphite. The Li-ion batteries have the advantage of high specific energy, as well as high energy and power density relative to other battery technologies. They also exhibit a high rate and high-power discharge capability, excellent round-trip efficiency, relatively long lifetime and a low self-discharge rate. Issues relating to the thermal stability and safety of Li-ion batteries relate to chemical reactions that release oxygen when lithium metal oxide cathodes overheat. This "thermal runaway" may cause leaks, smoke gas venting and may lead to the cell catching fire. While this is an inherent risk of this battery type, it can be triggered by external non-design influences such as external heat conditions, overcharging, discharging or high-current charging. /10/

There are five different types of lithium-ion batteries, such as Lithium nickel manganese cobalt oxide, lithium manganese oxide, lithium nickel cobalt aluminum, lithium iron phosphate and lithium titanate (see Figure 5.) All these types of Li-ion batteries have an energy density between 200 and 735 Wh/l and a round-trip efficiency of 92-96%. /10/

Key active material	lithium nickel manganese cobalt oxide	lithium manganese oxide	lithium nickel cobalt aluminium	lithium iron phosphate	lithium titanate
Technology short name	NMC	LMO	NCA	LFP	LTO
Cathode	$LiNi_xMn_yCo_{1-x-y}O_2$	$LiMn_2O_4$ (spinel)	$LiNiCoAlO_2$	$LiFePO_4$	variable
Anode	C (graphite)	C (graphite)	C (graphite)	C (graphite)	$Li_4Ti_5O_{12}$
Safety					
Power density					
Energy denisty					
Cell costs advantage					
Lifetime					
BES system performance					
Advantages	-good properties combination -can be tailored for high power or high energy -stable thermal profile -can operate at high voltages	-low cost due to manganese abundance -very good thermal stability -very good power capability	-very good energy and good power capability -good cycle life in newer systems -long storage calendar life	-very good thermal stability -very good cycle life -very good power capability -low costs	-very good thermal stability -long cycle lifetime -high rate discharge capability -no solid electrolyte interphase issues
Disadvantages	-patent issues in some countries	-moderate cycle life insufficient for some applications -low energy performance	-moderate charged state thermal stability which can reduce safety -capacity can fade at temperature 40-70°C	-lower energy density due to lower cell voltage	-high cost of titanium -reduced cell voltage -low energy density

Figure 5. Comparison of lithium-ion chemistry properties, advantages and disadvantages. /10/

3.3.5 Sodium-Sulphur Battery

The Sodium-Sulphur battery is one of the more recent battery technologies that shows great promise for high-power energy storage applications. It is made of metallic sodium (Na) anode and sulphur (S) cathode. While a ceramic Beta-Al_2O_3 acts as both the electrolyte and the separator simultaneously. This battery type has no self-discharge, energy density and the efficiency are quite high at 151 W/l and 85% respectively. /7/

3.3.6 Flow Batteries

Unlike other battery types, flow batteries store electrolytes in two separate tanks. One tank has the anodes and the other one has the catholytes. These two tanks are separated from the regenerative cell stack where reversible electrochemical reaction occur during charging and discharging the system /10/. During the battery charging process in flow batteries, the electrolyte in one tank is oxidized at the anode, while the electrolyte in the other tank is reduced at the cathode. This process is reversed during the discharging phase. The three common types of flow batteries that are currently commercially available are vanadium redox batteries (VRB), zinc bromide batteries (ZBB) and polysulphide bromide batteries (PSB) /7/. Flow batteries have several distinct advantages, such as they can operate at close to ambient temperatures, independently scale their energy and power characteristics, good lifetime, relatively cheap, very deep discharge rates without greatly impacting the lifetime and have good safety characteristics. The disadvantages of flow batteries include low efficiency when compared against a lithium-ion battery and its complex system structure. /10/

4 RESERVE MARKET

Finland's energy reserve market plays a vital role in the country's energy system. It is designed to ensure the reliability of the electricity system during sudden disturbances or outages. The self-dispatch model serves as the foundation for the market design. Fingrid, as the Finnish transmission system operator, manages the Finnish power transmission system located in Northern Europe, which forms part of the Nordic synchronous area. This consist of the transmission systems of eastern Denmark, Finland, Norway and Sweden, collectively making up the Nordic LFC block. Within Fingrid's control area, there is only one scheduling and one bidding zone, providing a unified framework for the management and operation of the Finnish power transmission. /11/

4.1 Reserve types

The Nordic synchronous area utilizes two types of reserves, namely FCR and FFR, to maintain balance within the system. FCRs are primarily used to regulate frequency and are subdivided into three products, namely FCRN, FCRD up and FCRD down. The latest addition to the reserve products used in the Nordic synchronous area is FCRD own, which Fingrid began procuring on January the 1st 2022. The process of frequency containment is responsible for stabilizing the frequency of the power system after a disturbance. This is achieved by bringing the frequency to a steady-state value within the maximum permissible frequency deviation, through a coordinated effort of the FCR across the entire synchronous area. Conversely, FFRs aim to restore the frequency to the nominal value of 50,0 Hz and release the activated FCRs. These reserves are segregated into two reserve products, namely aFRR and mFRR. Replacement reserves are not in use within the Nordic synchronous area. /11/

4.1.1 FCR

The frequency containment reserve for normal operation (FCR-N) and frequency containment reserve for disturbances (FCR-D) are dynamic active power reserves that automatically adjust based on the frequency deviation of the power system. Their primary role is to regulate the frequency during both normal operation and disturbances. FCR-N is specifically designed to keep the frequency within the standard range of 49,9Hz to 50,1Hz. On the other hand, FCR-D serves to restrict the frequency deviation to a minimum of 49,5 Hz or a maximum of 50,5 Hz when the frequency falls outside the standard range. /12/

4.1.2 FFR

The procurement of fast frequency reserve (FFR) is crucial in the situations where the power system experiences low inertia. Inertia, in this context refers to ability of the kinetic energy stored in the rotating masses of the electricity system to resist frequency changes. To ensure system stability, the power system follows a dimensioning principle, which mandates that the loss of a single electricity production unit or HVDC link should not cause the frequency to drop below 49.0 Hz. The extent of the transient frequency change after a disturbance depends on various factors, including the magnitude of the power change, system inertia, and the speed at which reserves are activated. The volume of FFR needed, is dependent on the level of inertia in the power system and the size of the reference incident. Since May 2020, the implementation of the FFR has been operational in the Nordics. Fingrid procures the reserve from a national market and to participate, the balancing service provider must complete the prequalification process of the reserve unit and sign the FFR market contract. /18/

4.1.3 aFRR

The Nordic Transmission System Operators established the Automatic Frequency Restoration Reserve in 2013. Its purpose is to return the frequency to the nominal

value of 50Hz. aFRR is a centrally operated reserve that responds automatically to an activation request signal sent by the TSO every 10 seconds, based on the frequency deviation in the Nordic synchronous region. The minimum capacity of regulation is 1MW and the full activation time is 5 minutes maximum. /17/

Fingrid buys aFRR reserve from the hourly market and other Nordic countries through inter-TSO trades. Fingrid notifies in advance of the procurement hours. Balance service providers can submit bids for up-regulation and down-regulation capacities separately on the hourly market, and the capacity payment is based on the highest accepted bid price. The balance responsible party of the reserve resource receives a separate energy fee for actual regulation energy, with the energy fee for up-regulation determined by the balancing energy market price for up-regulation and the activation price for down-regulation determined by the balancing energy market price for down-regulation. /17/

A common Nordic aFRR market is expected to be introduced in the future, and a project for a common European aFRR energy market is ongoing. /17/

4.1.4 mFRR

Fingrid, along with other Nordic transmission system operators, operates a balancing energy market. To participate in this market, a reserve provider must offer an amount of up-regulating bids equivalent to their accepted capacity bids and enter into a balancing energy market contract with Fingrid. The Nordic TSOs manually activate bids on the balancing energy market as necessary during regular operation or disruptions. /16/

The balancing capacity market, introduced in 2016, requires reserve providers with accepted capacity bids to offer up-regulating energy bids in exchange for financial compensation. This market is used to ensure that Fingrid has an adequate amount of Manual Frequency Restoration Reserve to cover fault dimensioning,

including during maintenance of Fingrid's reserve power plants, as well as leasing reserve power plants. /16/

4.2 Reserve Market Producer

To participate in the reserve market (see Figure 6), one must either be the owner of an adjustable resource or a part of the open electricity supply chain, either as an electricity seller or a balance responsible party. Currently, even an external party outside of the open supply chain can act as a reserve provider in the FFR, FCR-D (Up and down separately) and FCR-N. If the reserve provider is not the owner of the resource, they must have the owner's permission to use the resource for adjustment purposes. If the reserve provider is not the balance responsible party for the resource, the balance responsible party must be informed of the adjustment use. /13/

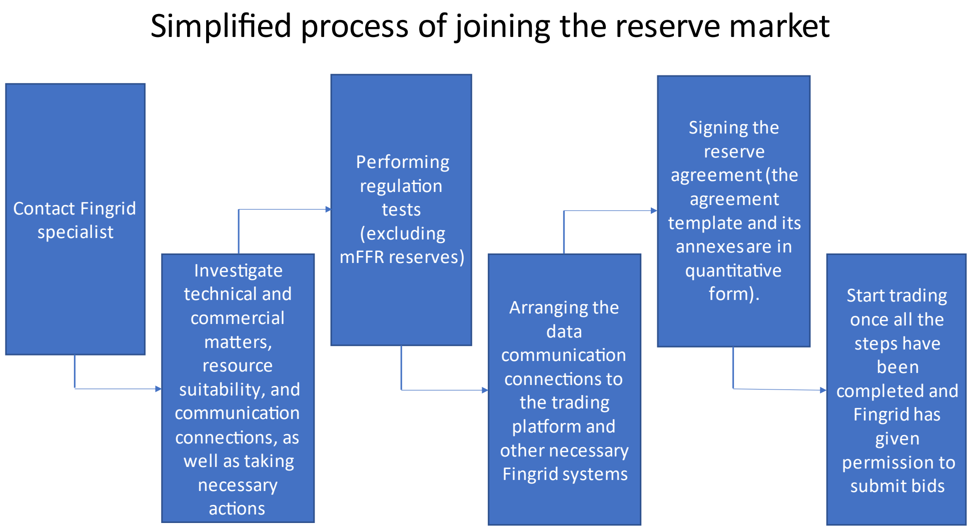

Figure 6. Process of joining the Finnish energy reserve market. /13/

5 RESEARCH METHOD

A business case was used as the research method. A business case presents a well-supported recommendation to executive decision-makers regarding a proposed project, policy, or program that requires resource allocation, frequently with a financial component. It is a persuasive argument based on evidence and analysis to justify the need for the investment. /15/

Project planning commences only after the business case confirms the feasibility of the project. The research and data collected during the business case study can be leveraged during the business planning stage to save time on research. A comprehensive business case analysis can provide a wealth of information that is vital to the business plan. The project sponsors rely on the outcome of the business case to decide whether to finance the project or not. Recommendations are based on a blend of numerical data and qualitative, experience-based insights. A successful business case study heavily relies on thorough market research and analysis to provide stakeholders with varying degrees of evidence that a business concept will be viable. A compelling business case serves as a valuable instrument to secure approval for a project from those with authority. Within the business case, the rationale for proposing the project is substantiated by outlining the quantifiable advantages it will offer the organization, the expenses involved, the projected return of investment, as well as how the project aligns with other initiatives and the overarching corporate strategy.

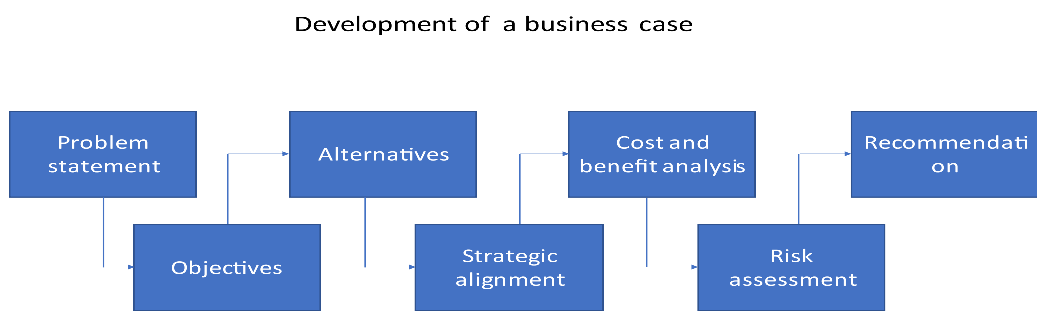

Figure 7. Business case development.

6 BUSINESS CASE SOLAR PV + BESS

The business case for this thesis is the feasibility calculation for a 5MWp PV powerplant in connection with a battery energy storage system. The site for this project is in Raahe, Northern Ostrobothnia. The site surface area is roughly 8,5 hectares, whereof 2,3 hectares are covered by solar panels to produce a peak power of 4976 kW. The BESS specifications were received from a supplier who wants to stay anonymous for the time being.

For utility-scale systems, two main PV + BESS configurations are currently in use: AC-coupled and DC-coupled. In this business case, an AC-coupled system was used (Figure 8).

No interest or taxes have been assumed in these calculations. The result focuses on the EBIT that could be received from the different cases that are calculated.

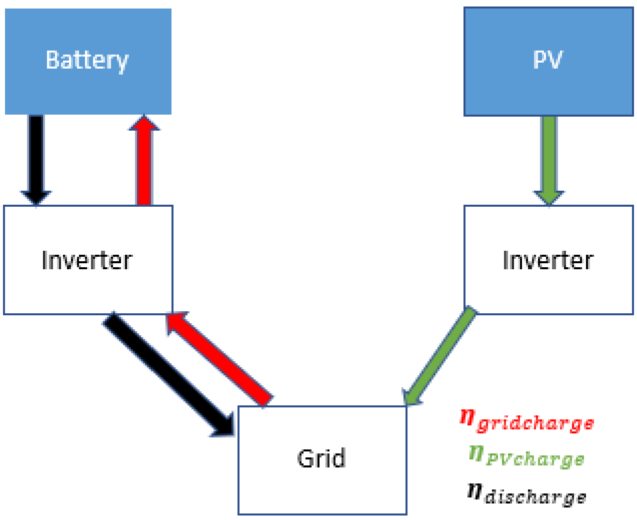

Figure 8. AC Coupled system.

6.1 Standalone PV

The business case of standalone PV is presented in Figure 9. The key assumptions of the business case can be seen in Table 1.

Table 1. List of assumptions for standalone PV.

Assumptions	**Reason**
Inflation	The inflation is assumed to be 1,5%. The electricity and all operational costs have been adjusted for inflation except for the property tax.
PV production	The production calculations were made by using PVsyst, these are also assumptions because it’s hard to predict exactly the amount of sun per year.
Electricity price	Assuming that the average of the electricity price will be 54€/MWh during the first year.

The capex for the whole Solar photovoltaic powerplant is 3,1 million euros and Business Finland’s subsidies which could cover 15% of the funding for the equipment and planning but not the grid connection fee. The investment would be 2,65 million euros. As shown below Table 2 the investment would get almost 4,5 million euro EBIT during the 30-year lifetime of the solar panels.

Table 2. Business case calculations for standalone PV

Revenue	Units										
Year		1	2	3	4	5	6	7	8	9	10
Produced	MWh	4719	4701	4681	4658	4633	4604	4571	4536	4502	4469
Electricity price	€/MWh	54,0 €	54,8 €	55,6 €	56,5 €	57,3 €	58,2 €	59,0 €	59,9 €	60,8 €	61,7 €
Total revenue per year		254 826 €	257 662 €	260 414 €	263 022 €	265 534 €	267 830 €	269 899 €	271 850 €	273 859 €	275 930 €
Lifetime revenue		8 688 124 €									
Balance handling and transmission costs		12 741 €	12 883 €	13 021 €	13 151 €	13 277 €	13 392 €	13 495 €	13 592 €	13 693 €	13 796 €
Insurance		5 000 €	5 075 €	5 151 €	5 228 €	5 307 €	5 386 €	5 467 €	5 549 €	5 632 €	5 717 €
Land		5 100 €	5 177 €	5 254 €	5 333 €	5 413 €	5 494 €	5 577 €	5 660 €	5 745 €	5 831 €
Property tax		12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €
O&M		10 000 €	10 150 €	10 302 €	10 457 €	10 614 €	10 773 €	10 934 €	11 098 €	11 265 €	11 434 €
Depreciation expenses		88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €
OPEX		133 329 €	133 773 €	134 216 €	134 657 €	135 098 €	135 533 €	135 961 €	136 388 €	136 823 €	137 267 €
total OPEX		4 203 574 €									
EBIT		4 484 550 €									

6.2 Standalone BESS

The business case for the standalone BESS is show in the figure 10. Key assumptions are shown in Table 3.

Table 3. List of assumptions for standalone BESS.

Assumptions	Reason
Inflation	The inflation is assumed to be 1,5%. The electricity and all operational costs have been adjusted for inflation except for the property tax.
Insurance	Assuming the insurance will be 0,5% of the capex per year
Electricity price	Assuming the average of the electricity sold price will be 65€/MWh during the first year and that the electricity bought will be 20€/MWh.
Operations and maintenance	Assuming the O&M will be roughly 1% of the capex

The capex for the standalone BESS is 1,16 million euros, Business Finland does not grant subsidies for this case as mentioned in chapter 6.4.1. The BESS was used only for energy arbitrage. This case relies heavily on the electricity price, but the unpredictability of its price does make it very difficult to make a valid assumption of the profitability. By using today's market prices, standalone BESS could not be made profitable. During the 15-year lifecycle of the BESS it would generate a negative EBIT of almost 1 million euro.

Table 4. Business case calculations for standalone BESS

Financial Assumptions	**Units**										
Year		1	2	3	4	5	6	7	8	9	10
Energy sold to the grid	MWh	876	858	841	824	808	792	776	760	745	730
Sold energy revenue		56 940 €	56 638 €	56 338 €	56 039 €	55 742 €	55 447 €	55 153 €	54 861 €	54 570 €	54 281 €
Cost of Energy Purchased		19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €
Balance handling and transmission costs		2 847 €	2 832 €	2 817 €	2 802 €	2 787 €	2 772 €	2 758 €	2 743 €	2 729 €	2 714 €
Insurance		5 800 €	5 887 €	5 975 €	6 065 €	6 156 €	6 248 €	6 342 €	6 437 €	6 534 €	6 632 €
Land		600 €	609 €	618 €	627 €	637 €	646 €	656 €	666 €	676 €	686 €
O&M		11 600 €	11 774 €	11 951 €	12 130 €	12 312 €	12 496 €	12 684 €	12 874 €	13 067 €	13 263 €
Depreciation Expenses		77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €
Total Operating Expenses		117 433 €	117 688 €	117 947 €	118 210 €	118 478 €	118 750 €	119 026 €	119 306 €	119 591 €	119 881 €
EBIT		-60 493 €	-61 050 €	-61 609 €	-62 171 €	-62 735 €	-63 303 €	-63 873 €	-64 446 €	-65 021 €	-65 600 €
Total EBIT		-967 097 €									

6.3 PV + BESS

The business case for the PV + BESS is shown in figure 11. Key assumptions are shown in Table 5.

Table 5. List of assumptions for the PV + BESS.

Assumptions	**Reason**
Inflation	The inflation is assumed to be 1,5%. The electricity and all operational costs have been adjusted for inflation
Insurance	Assuming the insurance will be 0,5% of the capex per year for the BESS.
Electricity price	Assuming the average of the electricity price for the energy sold from BESS will

	be 65€/MWh during the first year of operation. Assuming the electricity price for the PV production would be 54€/MWh
Operations and maintenance	Assuming the O&M for the BESS will be roughly 1% of the BESS capex

The capex for PV + BESS is 4,26 million euros and Business Finland's subsidies which will cover 15% of the funding for the equipment and planning but not the grid connection fee. This means that the investment cost would be 3,64 million euros for this project. The BESS was used for arbitrage only for this case. In this case the BESS lifetime is 15 years and the PV lifetime is 30 years. If the assumptions are correct for the time being, a 3,7-million-euro EBIT could be made with this project. The EBIT of 3,7 million euros is on a similar level as the total investment cost.

Table 6. Business case calculations for the PV + BESS.

Revenue	**Units**										
Year		1	2	3	4	5	6	7	8	9	10
Produced PV	MWh	3843	3843	3840	3834	3825	3812	3795	3776	3757	3739
Total revenue per year PV		207 522 €	210 609 €	213 610 €	216 466 €	219 225 €	221 766 €	224 079 €	226 273 €	228 524 €	230 835 €
Produced BESS	MWh	876	858	841	824	808	792	776	760	745	730
Total revenue per year BESS		56 940 €	56 638 €	56 338 €	56 039 €	55 742 €	55 447 €	55 153 €	54 861 €	54 570 €	54 281 €
Total revenue per year PV + BESS		264 462 €	267 247 €	269 948 €	272 505 €	274 967 €	277 213 €	279 233 €	281 134 €	283 094 €	285 116 €
Lifetime revenue		8 827 422 €									
Balance handling and transmission costs		13 223 €	13 362 €	13 497 €	13 625 €	13 748 €	13 861 €	13 962 €	14 057 €	14 155 €	14 256 €
Insurance		10 800 €	10 962 €	11 126 €	11 293 €	11 463 €	11 635 €	11 809 €	11 986 €	12 166 €	12 349 €
Land		5 100 €	5 177 €	5 254 €	5 333 €	5 413 €	5 494 €	5 577 €	5 660 €	5 745 €	5 831 €
Property tax		12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €
O&M		21 600 €	21 924 €	22 253 €	22 587 €	22 925 €	23 269 €	23 618 €	23 973 €	24 332 €	24 697 €
Depreciation expenses		154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €
OPEX		216 944 €	204 284 €	204 855 €	205 434 €	206 022 €	206 619 €	207 225 €	207 841 €	208 465 €	209 098 €
Total OPEX		5 131 294 €									
EBIT		3 696 128 €									

6.4 Available Subsidies

6.4.1 Business Finland Energy Funding

Business Finland provides funding for different renewable energy projects in Finland." The goal of energy support is to promote the use of renewable energy and increase energy efficiency. With energy support, investments that increase the use

or production of renewable energy can be made, or investments that promote energy savings can be made." /14/

For a solar PV project Business Finland is able to provide 15% of the funding if the energy production is a maximum of 5MW. They will also be able to fund the battery energy storage system, for a maximum amount of 15%. To be able to get the funding for the BESS, the cost of BESS must be less than 50% of the whole system investment. Projects related to BESS are only supported if there is also an investment in renewable energy production capacity.

7 DISCUSSION AND CONCLUSIONS

In conclusion, this thesis has explored the feasibility of solar PV and BESS for providing a good business case. The research showed that the PV + BESS is not as profitable as the standalone PV, when the BESS is only being used for energy arbitrage. Additionally, the reserve energy market was investigated to determine its operational procedures.

To answer the first research question, to make BESS feasible with solar PV, the Finnish reserve market would need to be made more profitable and the reserve market should be participated in instead of energy arbitrage with this kind of energy storage system. To answer the second research question, the reserve market in Finland works by using the self-dispatch model, which serves as the foundation for the market design and electricity producers and consumers can offer their reserve capacity for Fingrid.

This research was important for Etha Wind Oy as they are looking into providing energy storage options for their customers. The research showed us that the BESS is not profitable when standalone and that it makes the PV less profitable when compared to standalone PV.

The limitations for this thesis were drawn to not look too deep into the reserve market. Another limitation was that we did not do a business case for wind + BESS. Both subjects will be good ideas for future research.

Some of my own thoughts on this research are that the subject was good and interesting. The biggest problem we had during the research was getting the battery specifications from the battery suppliers, but luckily, we got one answer and based our research on those values. The BESS calculations were challenging because of the assumptions that had to be made.

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APPENDICES

Appendix1.

BESS Standalone

BESS specs	
Energy capacity	3
Power capacity	2
Roundtrip efficiency	91 %
Depth of discharge	80 %
Cycles per day	1

Rountrip efficiency		
Inverter losses	1,50 %	*Inverter losses will need to be used twice
Battery losses	5 %	
Transformer losses	1 %	

CAPEX				
BESS	Units	Quantity		Total Cost
Battery	Per MWh	3	370 000,00 €	1 110 000,00 €
Installation costs			50 000,00 €	50 000,00 €
Total investment cost				1 160 000,00 €

OPEX	Units	Total Costs	Assumptions
Land	€/Ha	600,00 €	
Insurance	€	5 800,00 €	0,5% of Capex
O&M	€	11 600,00 €	1% of Capex
Total Opex		18 000,00 €	

Energy Balance of BESS	Units	
Cycles per pay		1
Cycles per year		365
Depth of Discharge	%	0,80
Round Trip Efficiency	%	0,91
Power capacity	MW	2,00
Energy capacity	MWh	3,00
Duration	hr	1,50
Daily output energy	MWh	2,40
Daily input energy	MW/Day	2,64
Project life cycle	Years	15

Energy Generation	Units	
Total Generation per day	MW	2,4
Output Energy	MWh	876
Input energy	MWh	963
Energy lost	MWh	87
Charging cost	€/MWh	20,00 €

BESS Degradation	Units															
	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Output energy	MWh/Year	876,00	858,48	841,31	824,48	807,99	791,83	776,00	760,48	745,27	730,36	715,76	701,44	687,41	673,66	660,19
Degradation	%	2 %														

Electricity	Units															
	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Electricity price	€/MWh	65,00	65,98	66,96	67,97	68,99	70,02	71,07	72,14	73,22	74,32	75,44	76,57	77,72	78,88	80,06
Inflation	%	1,5 %														

Financial Assumptions	Units															
Year		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Energy sold to the grid	MWh	876	858	841	824	808	792	776	760	745	730	716	701	687	674	660
Sold energy revenue		56 940 €	56 638 €	56 338 €	56 039 €	55 742 €	55 447 €	55 153 €	54 861 €	54 570 €	54 281 €	53 993 €	53 707 €	53 422 €	53 139 €	52 858 €
Cost of Energy Purchased		19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €	19 253 €
Balance handling and transmission costs		2 847 €	2 832 €	2 817 €	2 802 €	2 787 €	2 772 €	2 758 €	2 743 €	2 729 €	2 714 €	2 700 €	2 685 €	2 671 €	2 657 €	2 643 €
Insurance		5 800 €	5 887 €	5 975 €	6 065 €	6 156 €	6 248 €	6 342 €	6 437 €	6 534 €	6 632 €	6 731 €	6 832 €	6 935 €	7 039 €	7 144 €
Land		600 €	609 €	618 €	627 €	637 €	646 €	656 €	666 €	676 €	686 €	696 €	707 €	717 €	728 €	739 €
O&M		11 600 €	11 774 €	11 951 €	12 130 €	12 312 €	12 496 €	12 684 €	12 874 €	13 067 €	13 263 €	13 462 €	13 664 €	13 869 €	14 077 €	14 288 €
Depreciation Expenses		77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €	77 333 €
Total Operating Expenses		117 433 €	117 688 €	117 947 €	118 210 €	118 478 €	118 750 €	119 026 €	119 306 €	119 591 €	119 881 €	120 175 €	120 475 €	120 778 €	121 087 €	121 401 €
EBIT		-60 493 €	-61 050 €	-61 609 €	-62 171 €	-62 735 €	-63 303 €	-63 873 €	-64 446 €	-65 021 €	-65 600 €	-66 182 €	-66 768 €	-67 356 €	-67 948 €	-68 543 €
Total EBIT		-967 097 €														

Standalone PV

PV Specs	Units	
Peak power	MWp	5
Production to grid	MWh/Year	4719

CAPEX	
PV powerplant cost	3 000 000,00 €
Business Finland subsidies	15 %
CAPEX Total after subsidies	2 550 000,00 €
Grid connection costs	104 640,00 €
CAPEX Total	2 654 640,00 €

OPEX	Units	Total Costs
Land	€/Ha	600,00 €
Insurance	€	5 000,00 €
O&M	€	10 000,00 €
Total Opex		15 600,00 €

Revenue	Units															
Year		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Produced	MWh	4719	4701	4681	4658	4633	4604	4571	4536	4502	4469	4440	4416	4394	4373	4353
Electricity price	€/MWh	54,0 €	54,8 €	55,6 €	56,5 €	57,3 €	58,2 €	59,0 €	59,9 €	60,8 €	61,7 €	62,7 €	63,6 €	64,6 €	65,5 €	66,5 €
Total revenue per year		254 826 €	257 662 €	260 414 €	263 022 €	265 534 €	267 830 €	269 899 €	271 850 €	273 859 €	275 930 €	278 251 €	280 898 €	283 691 €	286 571 €	289 539 €
Lifetime revenue		8 688 124 €														
Balance handling and transmission costs		12 741 €	12 883 €	13 021 €	13 151 €	13 277 €	13 392 €	13 495 €	13 592 €	13 693 €	13 796 €	13 913 €	14 045 €	14 185 €	14 329 €	14 477 €
Insurance		5 000 €	5 075 €	5 151 €	5 228 €	5 307 €	5 386 €	5 467 €	5 549 €	5 632 €	5 717 €	5 803 €	5 890 €	5 978 €	6 068 €	6 159 €
Land		5 100 €	5 177 €	5 254 €	5 333 €	5 413 €	5 494 €	5 577 €	5 660 €	5 745 €	5 831 €	5 919 €	6 008 €	6 098 €	6 189 €	6 282 €
Property tax		12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €
O&M		10 000 €	10 150 €	10 302 €	10 457 €	10 614 €	10 773 €	10 934 €	11 098 €	11 265 €	11 434 €	11 605 €	11 779 €	11 956 €	12 136 €	12 318 €
Depreciation expenses		88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €	88 488 €
OPEX		133 329 €	133 773 €	134 216 €	134 657 €	135 098 €	135 533 €	135 961 €	136 388 €	136 823 €	137 267 €	137 727 €	138 210 €	138 705 €	139 209 €	139 723 €
total OPEX		4 203 574 €														
EBIT		4 484 550 €														

Combined PV + BESS

CAPEX	
PV powerplant cost	3 000 000,00 €
BESS cost	1 160 000,00 €
PV+ BESS	4 160 000,00 €
Business Finland subsidies	15 %
CAPEX Total After subsidies	3 536 000,00 €
Grid connection costs	104 640,00 €
CAPEX Total	3 640 640,00 €

Revenue	Units															
Year		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Produced PV	MWh	3843	3843	3840	3834	3825	3812	3795	3776	3757	3739	3724	3715	3707	3699	3693
Total revenue per year PV		207 522 €	210 609 €	213 610 €	216 466 €	219 225 €	221 766 €	224 079 €	226 273 €	228 524 €	230 835 €	233 395 €	236 280 €	239 310 €	242 424 €	245 627 €
Produced BESS	MWh	876	858	841	824	808	792	776	760	745	730	716	701	687	674	660
Total revenue per year BESS		56 940 €	56 638 €	56 338 €	56 039 €	55 742 €	55 447 €	55 153 €	54 861 €	54 570 €	54 281 €	53 993 €	53 707 €	53 422 €	53 139 €	52 858 €
Total revenue per year PV + BESS		264 462 €	267 247 €	269 948 €	272 505 €	274 967 €	277 213 €	279 233 €	281 134 €	283 094 €	285 116 €	287 389 €	289 987 €	292 732 €	295 563 €	298 484 €
Lifetime revenue		8 827 422 €														
Balance handling and transmission costs		13 223 €	13 362 €	13 497 €	13 625 €	13 748 €	13 861 €	13 962 €	14 057 €	14 155 €	14 256 €	14 369 €	14 499 €	14 637 €	14 778 €	14 924 €
Insurance		10 800 €	10 962 €	11 126 €	11 293 €	11 463 €	11 635 €	11 809 €	11 986 €	12 166 €	12 349 €	12 534 €	12 722 €	12 913 €	13 106 €	13 303 €
Land		5 100 €	5 177 €	5 254 €	5 333 €	5 413 €	5 494 €	5 577 €	5 660 €	5 745 €	5 831 €	5 919 €	6 008 €	6 098 €	6 189 €	6 282 €
Property tax		12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €	12 000 €
O&M		21 600 €	21 924 €	22 253 €	22 587 €	22 925 €	23 269 €	23 618 €	23 973 €	24 332 €	24 697 €	25 068 €	25 444 €	25 825 €	26 213 €	26 606 €
Depreciation expenses		154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €	154 221 €
OPEX		216 944 €	204 284 €	204 855 €	205 434 €	206 022 €	206 619 €	207 225 €	207 841 €	208 465 €	209 098 €	209 742 €	210 394 €	211 057 €	211 730 €	212 412 €
Total OPEX		5 131 294 €														
EBIT		3 696 128 €														

Appendix 2.

Version 7.3.2

PVsyst - Simulation report

Grid-Connected System

Project: Thesis project

Variant: New simulation variant

Sheds on ground

System power: 4976 kWp

Palonkylä - Finland

Author
Etha Wind Oy Ab (Finland)

PVsyst V7.3.2
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Etha Wind Oy Ab (Finland)

Project summary

Geographical Site
Palonkylä
Finland

Situation

Latitude	64.64 °N
Longitude	24.50 °E
Altitude	6 m
Time zone	UTC+2

Meteo data
Palonkylä
PVGIS api TMY

Monthly albedo values

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Albedo	0.55	0.55	0.55	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

System summary

Grid-Connected System
Simulation for year no 1

Sheds on ground

PV Field Orientation
Fixed plane
Tilt/Azimuth 40 / 0 °

Near Shadings
According to strings
Electrical effect 100 %

User's needs
Unlimited load (grid)

System information

PV Array

Nb. of modules	9048 units
Pnom total	4976 kWp

Inverters

Nb. of units	12 units
Pnom total	4224 kWac
Pnom ratio	1.178

Results summary

Produced Energy	4717487 kWh/year	Specific production	948 kWh/kWp/year	Perf. Ratio PR	80.49 %

Table of contents

PVsyst V7.3.2
VCC, Simulation date:
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with v7.3.2

Project: Thesis project

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Etha Wind Oy Ab (Finland)

General parameters

Grid-Connected System | **Sheds on ground**

PV Field Orientation

Orientation		**Sheds configuration**		**Models used**	
Fixed plane		Nb. of sheds	176 units	Transposition	Perez
Tilt/Azimuth	40 / 0 °	**Sizes**		Diffuse	Imported
		Sheds spacing	10.5 m	Circumsolar	separate
		Collector width	4.58 m		
		Ground Cov. Ratio (GCR)	43.6 %		
		Shading limit angle			
		Limit profile angle	22.8 °		

Horizon	**Near Shadings**		**User's needs**
Free Horizon	According to strings		Unlimited load (grid)
	Electrical effect	100 %	

Bifacial system

Model: 2D Calculation, unlimited sheds

Bifacial model geometry		**Bifacial model definitions**	
Sheds spacing	10.50 m	Ground albedo	0.30
Sheds width	4.62 m	Bifaciality factor	70 %
Limit profile angle	22.8 °	Rear shading factor	5.0 %
GCR	44.0 %	Rear mismatch loss	10.0 %
Height above ground	1.50 m	Shed transparent fraction	0.0 %

PV Array Characteristics

PV module		**Inverter**	
Manufacturer	Longi Solar	Manufacturer	Sungrow
Model	LR5-72HBD-550M G2 Bifacial	Model	SG350HX
(Original PVsyst database)		(Custom parameters definition)	
Unit Nom. Power	550 Wp	Unit Nom. Power	352 kWac
Number of PV modules	9048 units	Number of inverters	12 units
Nominal (STC)	4976 kWp	Total power	4224 kWac
Modules	348 Strings x 26 In series	Operating voltage	500-1500 V
At operating cond. (50°C)		Pnom ratio (DC:AC)	1.18
Pmpp	4559 kWp	Power sharing within this inverter	
U mpp	982 V		
I mpp	4642 A		

Total PV power		**Total inverter power**	
Nominal (STC)	4976 kWp	Total power	4224 kWac
Total	9048 modules	Number of inverters	12 units
Module area	23373 m²	Pnom ratio	1.18
Cell area	21697 m²		

Array losses

Array Soiling Losses

Average loss Fraction 4.0 %

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
6.0%	6.0%	6.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	6.0%

Array losses

Thermal Loss factor
Module temperature according to irradiance
Uc (const) 20.0 W/m²K
Uv (wind) 0.0 W/m²K/m/s

DC wiring losses
Global array res. 3.5 mΩ
Loss Fraction 1.5 % at STC

Module Quality Loss
Loss Fraction -0.8 %

Module mismatch losses
Loss Fraction 2.0 % at MPP

Strings Mismatch loss
Loss Fraction 0.1 %

Module average degradation
Year no 1
Loss factor 0.45 %/year
Mismatch due to degradation
Imp RMS dispersion 0.4 %/year
Vmp RMS dispersion 0.4 %/year

IAM loss factor
Incidence effect (IAM): User defined profile

0°	25°	45°	60°	65°	70°	75°	80°	90°
1.000	1.000	0.995	0.962	0.936	0.903	0.851	0.754	0.000

System losses

Unavailability of the system
Time fraction 2.0 %
7.3 days,
3 periods

Auxiliaries loss
Night aux. cons. 2.00 kW

AC wiring losses

Inv. output line up to MV transfo
Inverter voltage 800 Vac tri
Loss Fraction 2.36 % at STC
Inverter: SG350HX
Wire section (12 Inv.) Copper 12 x 3 x 95 mm²
Average wires length 186 m

MV line up to Injection
MV Voltage 20 kV
Wires Alu 3 x 95 mm²
Length 120 m
Loss Fraction 0.05 % at STC

AC losses in transformers

MV transfo
Medium voltage 20 kV
Transformer from Datasheets
Nominal power 4400 kVA
Iron Loss (24/24 Connexion) 3.00 kVA
Iron loss fraction 0.07 % of PNom
Copper loss 29.00 kVA
Copper loss fraction 0.66 % at PNom
Coils equivalent resistance 3 x 0.96 mΩ

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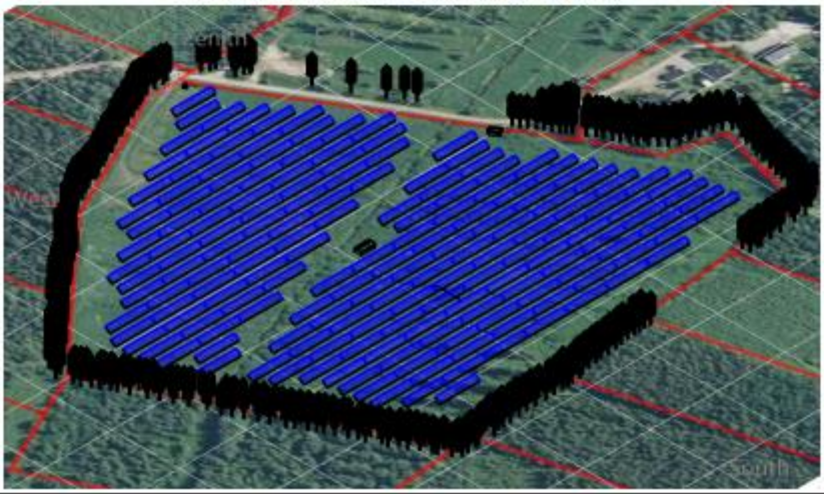
Etha Wind Oy Ab (Finland)

Near shadings parameter

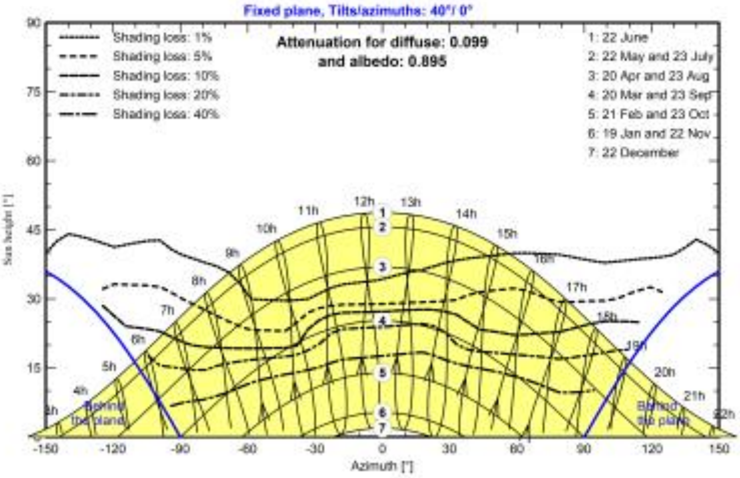
Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram

Orientation #1

Fixed plane, Tilts/azimuths: 40°/ 0°



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Main results

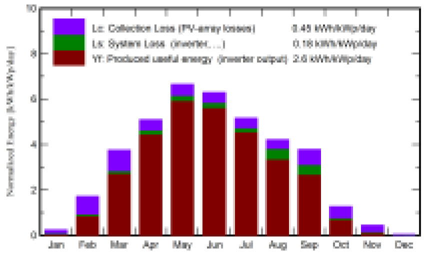
System Production

Produced Energy 4717487 kWh/year

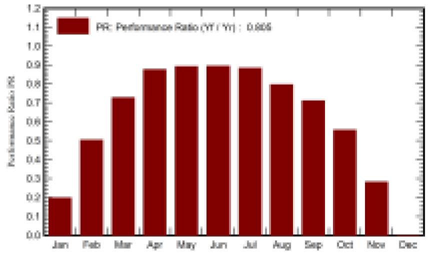
Specific production 948 kWh/kWp/year

Performance Ratio PR 80.49 %

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh
January	3.2	2.80	-5.08	7.5	3.0	14442
February	19.9	11.21	-6.83	48.2	27.0	130158
March	63.5	26.06	-1.14	116.5	93.2	439587
April	112.1	42.55	2.20	152.7	139.3	693113
May	177.7	57.57	6.84	206.2	189.6	950861
June	177.5	62.95	12.80	188.9	173.5	873587
July	146.3	64.23	15.26	160.0	146.2	732110
August	105.9	50.42	12.89	130.7	118.7	590175
September	68.4	29.07	11.05	113.5	99.2	465071
October	20.3	13.87	4.00	39.4	25.4	119586
November	4.7	3.43	1.29	13.2	5.3	24865
December	0.9	0.80	-0.68	1.3	0.5	2169
Year	900.4	364.96	4.45	1177.8	1020.7	5035725

Legends

GlobHor Global horizontal irradiation

DiffHor Horizontal diffuse irradiation

T_Amb Ambient Temperature

GlobInc Global incident in coll. plane

GlobEff Effective Global, corr. for IAM and shadings

EArray Effective energy at the output of the array

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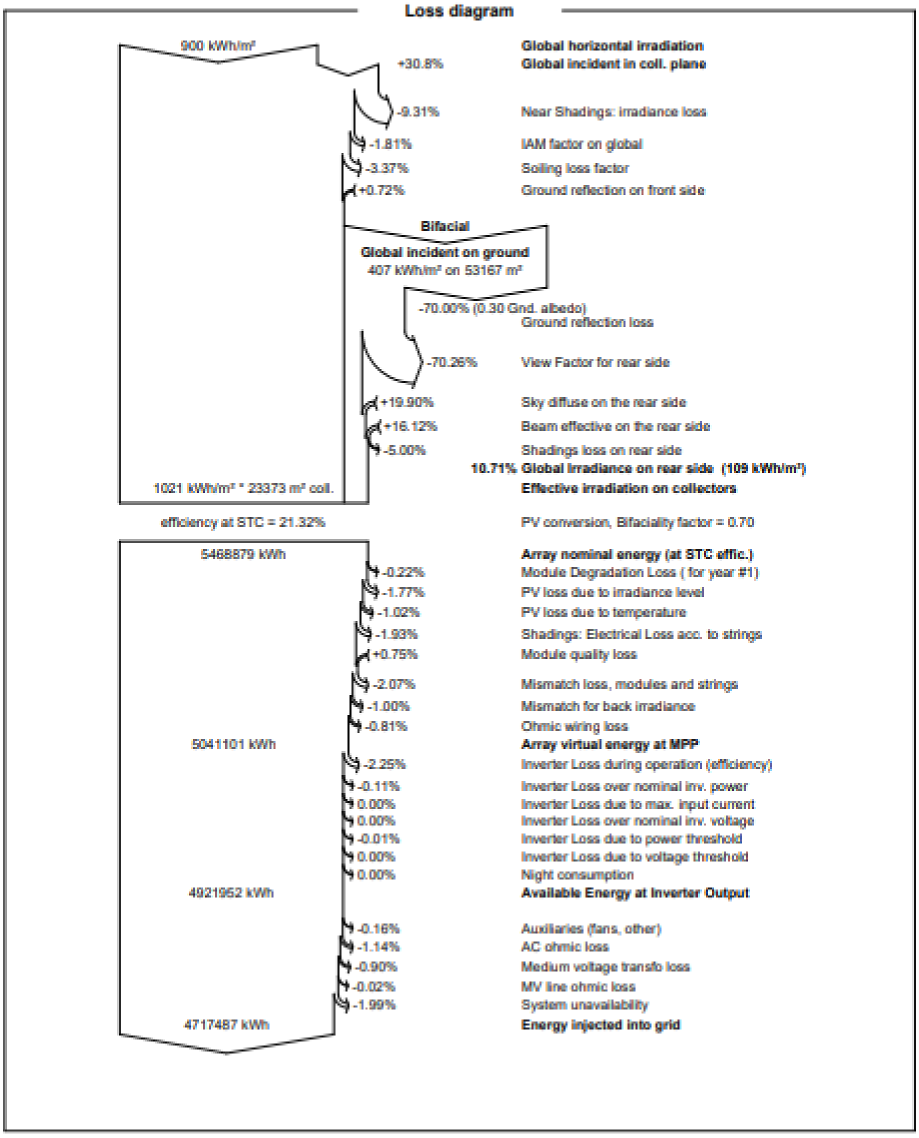
Loss diagram



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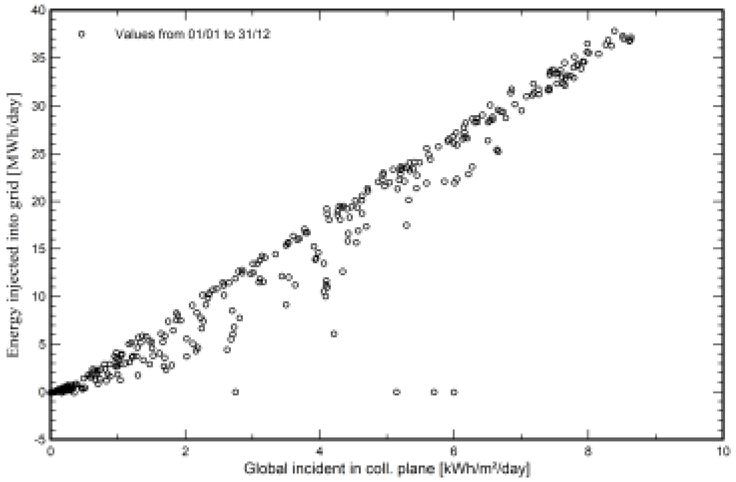
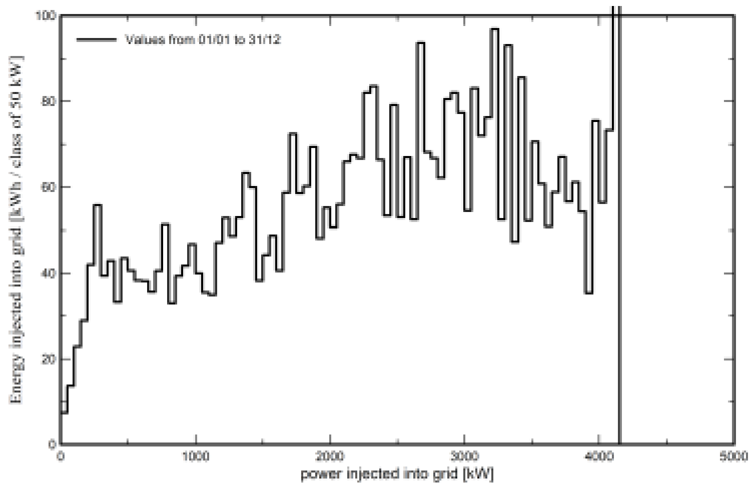
Predef. graphs

Daily Input/Output diagram



System Output Power Distribution



Aging Tool

Aging Parameters

Time span of simulation 30 years

Module average degradation

Loss factor 0.4 %/year

Mismatch due to degradation

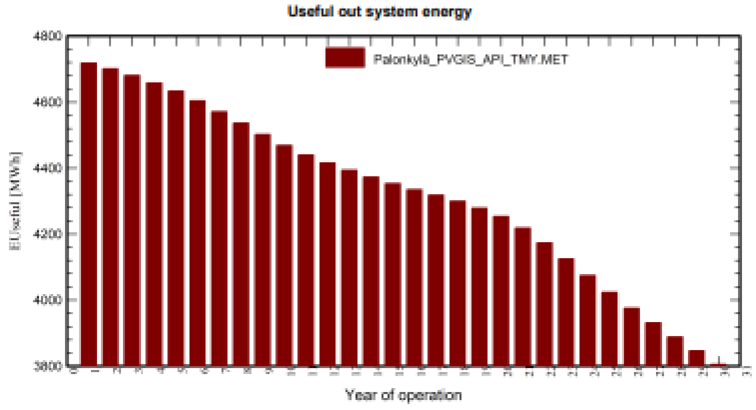
Imp RMS dispersion 0.4 %/year

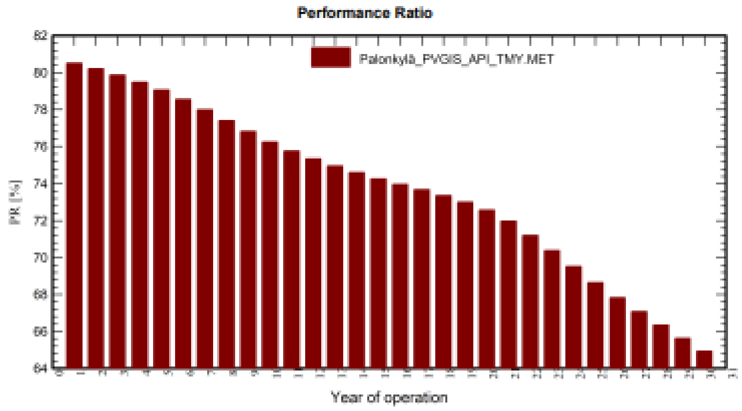
Vmp RMS dispersion 0.4 %/year

Meteo used in the simulation

Palonkylä PVGIS API TMY

Years reference year





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Aging Tool

Aging Parameters

Time span of simulation 30 years

Module average degradation

Loss factor 0.4 %/year

Mismatch due to degradation

Imp RMS dispersion 0.4 %/year

Vmp RMS dispersion 0.4 %/year

Meteo used in the simulation

Palonkylä PVGIS API TMY

Years reference year

	EUseful	PR	PR loss
Year	MWh	%	%
1	4719	80.51	-0.19
2	4701	80.21	-0.56
3	4681	79.87	-0.98
4	4658	79.48	-1.46
5	4633	79.06	-1.99
6	4604	78.55	-2.61
7	4571	77.98	-3.32
8	4536	77.40	-4.04
9	4502	76.81	-4.77
10	4469	76.24	-5.48
11	4440	75.75	-6.08
12	4416	75.35	-6.59
13	4394	74.97	-7.05
14	4373	74.61	-7.50
15	4353	74.27	-7.92
16	4335	73.96	-8.30
17	4318	73.68	-8.66
18	4300	73.36	-9.05
19	4279	73.00	-9.50
20	4253	72.57	-10.03
21	4218	71.97	-10.77
22	4173	71.21	-11.72
23	4125	70.38	-12.74
24	4075	69.52	-13.81
25	4023	68.65	-14.89
26	3975	67.83	-15.91
27	3931	67.08	-16.84
28	3888	66.34	-17.75
29	3846	65.63	-18.64
30	3806	64.93	-19.50

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Variant: New simulation variant

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P50 - P90 evaluation

Meteo data

Source	PVGIS api TMY
Kind	TMY, multi-year
Year-to-year variability(Variance)	8.0 %
Specified Deviation	
Climate change	0.0 %

Global variability (meteo + system)

Variability (Quadratic sum)	8.2 %

Simulation and parameters uncertainties

PV module modelling/parameters	1.0 %
Inverter efficiency uncertainty	0.5 %
Soiling and mismatch uncertainties	1.0 %
Degradation uncertainty	1.0 %

Annual production probability

Variability	387 MWh
P50	4717 MWh
P75	4457 MWh
P95	4082 MWh

Probability distribution