POLITECNICO DI TORINO

Master of Science Program Energy and Nuclear Engineering

Master Thesis

Planning of renewable sources and application case in Sri Lanka

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I would like to thank my supervisors Prof. Filippo Spertino and Prof. Alessandro Ciocia for all their help and advice with this thesis.

I would like to dedicate this thesis to my family, I am deeply grateful for their support and belief in me.

Torino, 23\03\2022

Francesco

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Introduction

Since 1800, human activities have been the main reason of climate change, which interests all countries of the World. The cause is attributable to the continuous use of fossil sources and the emission of greenhouse gases into the atmosphere [1]. As they often involve irreversible phenomena such as the increase in extreme phenomena and the increase in rainfall and winds, with catastrophic effects, everyone's commitment to achieve global goals is important. In 2015, thanks to the Paris agreement, the goal was set to keep the temperature rise below 2 °C compared to pre-industrial period [2]. The European Union has set itself the goal of reducing by 2030 its emissions by 55% respect to 1990, through the introduction of the "*Green Deal*", which represents the actions to be taken to achieve the results. Through the Glasgow agreement during COP-26 of 2021, the most developed countries will increase economic aid in order that developing countries will also be able to achieve their national objectives [3].

To reduce this problem, it is necessary to increase renewable sources in the energy mix, in particular with wind and photovoltaic systems, and to find storage systems capable of storing energy for long periods with high efficiency. For this type of technology to be competitive on the market, compared to the use of fossil fuels, is required an adequate incentive system by the State.

In this thesis work, the planning analysis of new plants for the production of electricity from renewable sources will be performed, such as wind and photovoltaic systems with an electrochemical storage system. For planning, the case study of a developing country in South Asia, Sri Lanka, will be analysed. In particular, the first part will evaluate the suitable installation sites for these plants, for this reason were assessed: the territorial constraints of the country, the presence of a transmission and distribution grid and the distribution of resources in the territory.

The first objective function that is analysed is the level of self-sufficiency. The goal is to find the optimal size of the generators, in order to satisfy the load and maximize self-sufficiency value. In this analysis, the economic parameters are selected as a constraint to be respected.

For the sizing of the systems, the Excel software was used, in which the RES_tool program is present that is capable of carrying out an energy and economic analysis, taking as input the meteorological data of the selected area. These data is downloaded on the PVGIS website, from which it is possible to obtain the hourly profiles of the main parameters, such as irradiance, mean wind speed and ambient temperature. The data are provided from 2005 to 2016, thus being able to observe not only a daily and seasonal variation but also an annual one. Furthermore, it is also necessary to have data on the hourly profiles of the electricity load for the analysed country. It is important to carefully consider the economic input data so as to evaluate solutions that are as real as possible. These parameters include the initial installation cost, the operation and maintenance cost and the discount rate applied to the investment. Furthermore, it is also important to correctly evaluate the cost of selling electricity and the value of self-consumed energy. Within the program there are models of the generators selected in order to estimate the productivity and perform an energy balance. Through this program it is possible to find the optimal size of the photovoltaic system to be installed, the number of wind turbines and the battery capacity, respecting all the imposed constraints, both physical and economic.

The optimization phase will be also performed using sensitivity analysis, through which it will possible to obtain the optimal plant configuration in order to maximize self-sufficiency value. With this procedure it is possible to observe how the main parameters of the project change when the input data is modified: in particular, the size of the generators selected is changed and the configuration that returns the highest value of self-sufficiency is found.

Subsequently, the system will be analysed in order to obtain the optimal solution that would maximize the economic return on investment. For this analysis, the parameter to be observed will be the value of the NPV (*Net Present Value*) and the value of the IRR (*Internal Rate of Return*).

Chapter 1

1 Introduction of planning & general aspects and models of RES technology

1.1 Planning Analysis

In this thesis work is performed the planning analysis for the development of renewable sources. In particular, the installation of wind and photovoltaic power systems and an electrochemical storage system will be analysed.

Through planning it is possible to estimate the optimal size of these plants and obtain economic information on the project in order to analyse its profitability. The solutions found will also have to respect some fixed physical constraints.

The steps performed in this work are summarized in the flow chart of *Figure 1.1*. In this work, planning analysis is applied to the Sri Lankan case study.

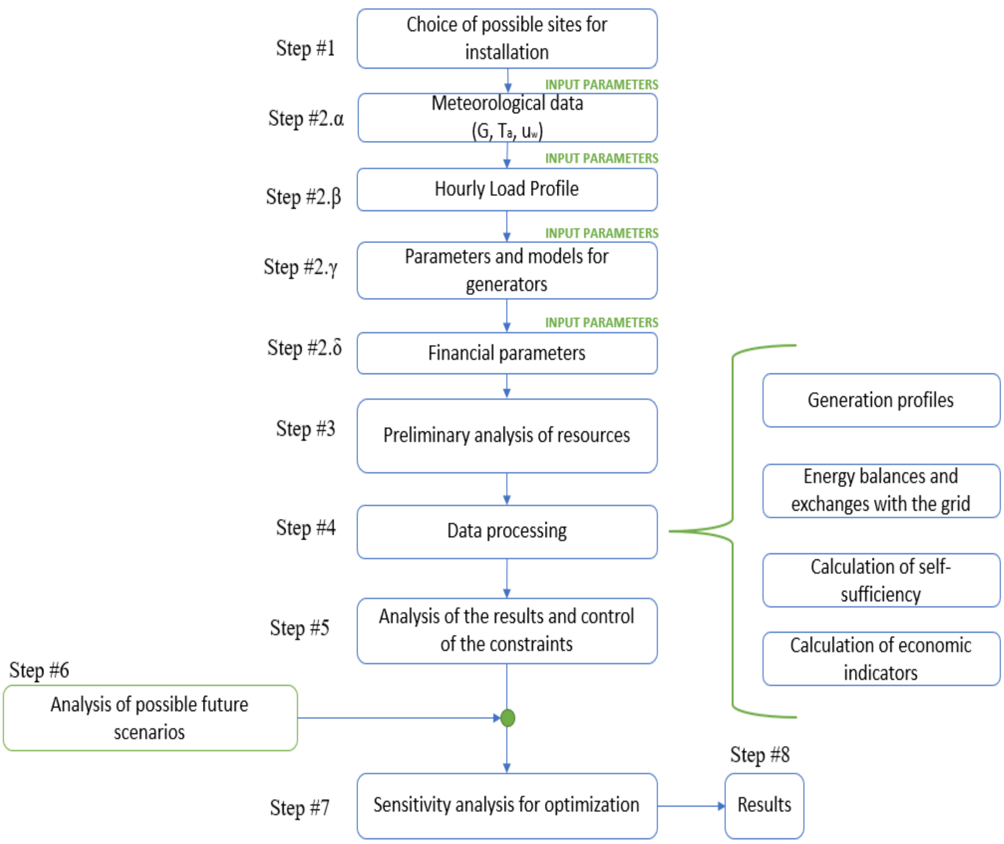

Figure 1. 1 Flow Chart of Energy Planning Analysis

Step # 1

In the first step, the energy context of the case study has been studied , the possible physical and territorial constraints were evaluated and the availability of resources in the territory was analysed. Through this process it is possible to identify sites where the installation of generators is suitable.

Step # 2.α

For the planning phase it is important to know the meteorological data of the installation sites, in particular it is necessary to have data on irradiance, mean wind speed and ambient temperature.

Step # 2.β

It is necessary to know the electrical load data on an hourly basis. This data is important for carrying out energy balances correctly. The electrical load differs according to the type of users, but it can be assumed that the electrical load given is used for an aggregate of different types of users.

Step # 2.γ

In this step, the systems are modelled. Through these models it is possible to represent the operation of the generators and it is also necessary to define some characteristic parameters that describe its functioning in particular situations.

Step # 2.δ

In this phase, all the financial data useful for calculating the economic indicators are defined. The main financial data include the investment cost, the operation and maintenance cost (O&M cost) and the discount rate of the investment. It is also important to define the selling price of electricity and eventually include various incentive schemes. It is also necessary to define the price of self-consumed electricity.

Step # 3

Through a preliminary analysis of the resources it is possible to analyse the distribution of the wind and solar resources in the territory and identify possible scenarios useful for the planning phase.

Step # 4

In this step all the data are processed and the main indicators useful for the planning phase are calculated. Initially, the productivity of the PV generators and WTs is calculated, then the balances with the electrical load are carried out. Through these data is calculated the level of self-sufficiency of the system. Finally, the economic indicators, that show the economic return on the investment, are evaluated. The main economic indicators are the NPV (*Net Present Value*) and IRR (*Internal Rate of Return*).

Step # 5

The solutions found after step #4 represent mathematically valid solutions, it is necessary to check the data obtained, in order to understand if the solutions found also respect the physical and economic constraints and are consistent with the goal to be achieved.

Step # 6

In this phase, possible future scenarios were researched, in particular on financial data and on the price of electricity, to obtain information for a possible future trend.

Step # 7

The sensitivity analysis is performed. Through this analysis it is possible to optimize both energy and economic parameters, evaluating how the main results change when an input parameter is modified.

Step # 8

In the last step, the results are obtained and evaluate which scenario allows to optimize the objective function set.

1.2 Self-sufficiency and self-consumption

In the energy analysis it is important to define the concept of self-sufficiency and self-consumption:

Self-Consumption represents the percentage of electricity generated by the system that is used to cover the load [4].

Self-Sufficiency represents the percentage of electricity demand that is covered by local generation [4].

With equations (1.1) and (1.2) it is possible to calculate the SC and SS indicators which quantify the level of self-consumption and self-sufficiency respectively:

$$SC = \frac{E_{load} - E_{absorption,grid}}{E_{local\ production}} \tag{1. 1}$$

$$SS = \frac{E_{load} - E_{absorption,grid}}{E_{load}} \tag{1. 2}$$

The difference between the load and the electricity absorbed from the grid ($E_{load} - E_{absorption,grid}$) represent the value of the energy locally produced by the system and used by the load. In this case the value refers both to the case in which this energy is immediately used, and in the case in which it is stored in the storage system and subsequently used.

Generally, an oversized system is able to produce a lot of energy consequently the value of self-sufficiency is high. However, with an oversized system, the extra energy produced is fed into the grid, consequently the value of self-consumption is low. The opposite is the case in which the plant is undersized. it is important to take this analysis into consideration when trying to size a plant, trying to find a high value for the two parameters.

In *Figure 1.2* the electricity demand is represented by the red curve, while the yellow curve represents the energy produced by a local generator, for example a photovoltaic system. Production is concentrated between 7:00 and 16:00 in which solar radiation is present. The area in green represents the minimum between the energy produced by local generators and the load. When the PV generator produces electricity, part of this energy is used directly to power the local load. The excess energy can be stored in storage systems or fed into the grid. The load that is not satisfied by the local generation, absorbed energy by the grid. By calculating self-sufficiency, it is possible to analyse how the local generator is able to satisfy the load to which it is connected. Self-sufficiency is defined as the ratio between the electricity produced in a given site and the energy that is consumed in the site itself, both instantaneously and through the storage systems. In this definition it is very important to correctly define the analysed site which must be properly defined and confined. In this analysis it is not important whether the producer and the final customer are the same subject, but it is important that the generator is connected directly to a well-defined load.

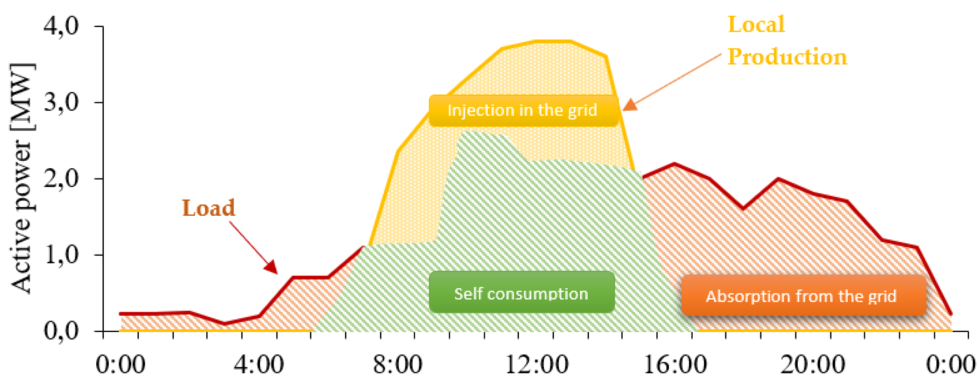

Figure 1. 2 Representative load and generation profiles

Increasing the percentage of self-sufficiency has numerous benefits, both economic and environmental occurs. As for the grid, the main advantages are:

- *Reduction of grid losses*: the use of generators directly connected to the load significantly reduces the losses of electricity related to transmission and distribution systems. Among the main causes of these losses is the Joule effect. In addition, there are various losses also due to the transformation of electricity, which in order to be properly transported from the generator to the final load undergoes voltage changes.

- *Reduction of investment costs*: the costs of building the distribution and transmission grid are very expensive. The creation of new grid or the expansion of existing grid has a significant impact on the return of the investment of the new projects. The creation of systems connected directly to the load allows to reduce this cost.

In this context, it is clear how important is the maximization of self-sufficiency, for this reason it is appropriate that the load profiles are as similar as possible for the generation profile. To encourage self-sufficiency, it is necessary that passive consumers become active users, therefore able not only to consume electricity but to produce part of their needs. Renewable energy systems, such as wind and photovoltaic generators, allow this kind of configuration, also reducing dependence on fossil fuels.

The main problem of the renewable sources are the uncertainty and uncontrollability of the source. For this reason, to increase the level of self-sufficiency it is necessary to use storage systems for the energy produced in excess by the generator, to be subsequently used in the periods in which the source is unable to satisfy the load, thus reducing the quantity of electricity absorbed by the grid.

To optimally adapt the generation curve to the load, in addition to the use of storage systems, it is possible to diversify the generation system. For example, a correctly sized photovoltaic system could satisfy the load during the day, while a wind system could satisfy the users during the night hours in which the production of energy from the photovoltaic system is zero. This type of configuration is advantageous if the wind and photovoltaic generation profiles are not simultaneous.

Another mechanism to increase the self-sufficiency is to adapt the load to the generation. In particular, through correct incentive systems, it is possible to reduce demand peaks and have a more constant demand curve. Furthermore, the reduction of peak consumptions allows to obtain more stable systems, as the imbalance between supply and demand could lead to power quality problems in the distribution system.

For a passive consumer, who decides to install local production systems, the main advantage is the reduction of the electricity purchased from the grid and it could also sell the surplus energy to the grid at an incentive price.

Increasing the percentage of self-sufficiency has several general advantages, both technical related to the reduced use of the grid, economic due to the reduction of the purchase of electricity from the grid, and environmental for the diffusion of renewable energy system with low emissions of pollutants.

1.3 General aspect of PV system

Photovoltaic systems (PV) are a system capable of producing electricity without the consumption of fossil sources, but by exploiting the solar radiation that reaches the Earth. During its operation it has no CO_2 emissions into the atmosphere. Solar energy is a renewable energy source because it is not subject to exhaustion, i.e., it re-integrates into nature on a human time scale. The main disadvantage of this technology is the uncertainty on the production, due to the intermittency and the uncontrollability of the solar source. A further disadvantage is the low conversion yields and requires an extensive installation area.

1.3.1 Solar radiation

Numerous thermonuclear reactions take place inside the Sun, which release energy, and its temperature reaches 5800 K. Part of this energy is then emitted by the star in the form of solar radiation. The Sun can be represented as a black body, that is an ideal emitter of radiation. The power emitted per unit area is a function of the wavelength, the radiation has a spectral distribution g_0, from ultraviolet to infrared. The maximum power is in the range of the visible to the human eye or with a wavelength of about 0.5 μm. The solar radiation propagates in the space in the form of an electromagnetic wave, and part of it reaches the earth's atmosphere, with which it enters into interaction. One part is reflected or dispersed, while another part is absorbed by the molecules in the atmosphere. The remainder parts reach Earth. The integral of the radiation per unit area is called solar irradiance. Also note how even the radiation that is diffused from the atmosphere manages to reach the earth's surface even if not directly; and some of the reflected radiation could also reach the surface of the Earth. The global irradiance that reaches the Earth is given by the sum of the three components: direct, diffuse and reflected.

This energy does not assume a constant value, but depends on numerous factors, for example the conditions of the atmosphere, the distance between the Sun and the Earth, the inclination of the Earth. The energy measured on the earth's surface depends on the place of installation and various measurements are required to evaluate the energy that can be used in that area by a photovoltaic system.

1.3.2 Photoelectric effect

The photovoltaic effect is the effect between the interaction of an electromagnetic wave with a valence electron of a semiconductor material. Valence electrons are the electrons that allow the formation of chemical bonds. In the theory of electronic band structure, valence electrons are those that are on the last available energy level, among those completely occupied. The conduction band, on the other hand, represents the lowest energy level among the bands not completely occupied by electrons. An electron could therefore pass from the valence band to the conduction band, leaving a hole within the valence band, which can be represented as a positive charge, compared to the electron which instead has a negative charge. *Figure 1.3* shows a diagram of the movement of electrons in three types of different materials. As can be seen in conducting materials (metals), the difference between the valence band and the conduction band is minimal. For semiconductor materials the two bands have an energy difference of about 1 eV, the *Energy gap*. For insulators, on the other hand, the energy required is greater.

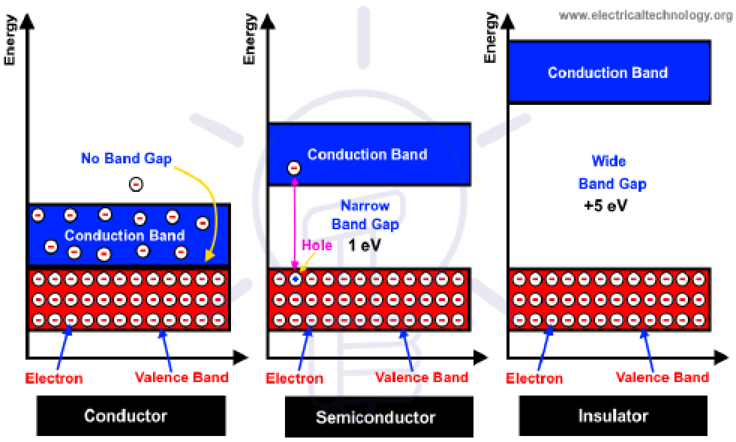

Figure 1. 3 Diagram of the electronic band structure for conductors, semiconductors and insulator materials [5]

Electromagnetic radiation not only has an wave nature, but it is composed of energy particles with zero mass, called *photons*. The energy possessed by the flow of particles is given by Plank's formula:

$$E_{ph} = \frac{h \cdot c}{\lambda}$$

(1. 3)

The energy to switch from one band to another is called the *Energy Gap*. In semiconductor materials this energy could be supplied to electrons by the interaction with electromagnetic waves. This mechanism is called the *photoelectric effect*. The interaction of the radiation with the semiconductor material then takes place and this can cause the emission of electrons from the surface of the material.

1.3.3 Solar cell

A solar cell is made up of semiconductor material, in commercial cells the most used material is crystalline silicon, which can be monocrystalline, polycrystalline or amorphous. Another technology used involves the superimposition of different materials with different Energy Gaps called Thin Films.

A solar cell is a semiconductor diode, as it is capable of passing electric current in only one direction. In a solar cell, the diode is located between two electrodes, where the upper one allows the passage of electromagnetic radiation. The diode is made by creating a *P-N junction* between the two electrodes. A substrate is then created which is doped with the introduction of trivalent atoms such as Boron (Type P) in which a doped layer with pentavalent atoms such as Phosphorus (Type N) is subsequently deposited. A distribution of negative charges in the P layer and positive charges in the N layer is created. With this mechanism a potential barrier is created, which contrasts the phenomena of diffusion of electrons, which naturally move from areas of high concentration to areas of low concentration. A condition of equilibrium is created, because the drift current, that is the one generated by the electric field of the junction, balances the diffusion current created by the difference in concentration.

Figure 1.4 shows the structure of a solar cell made up of polycrystalline silicon.

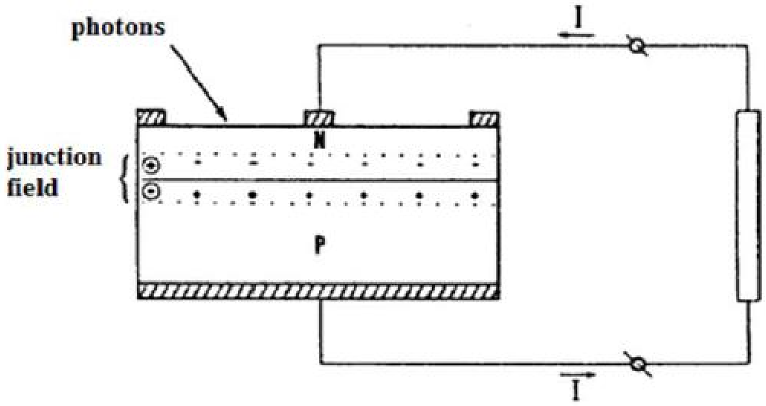

Figure 1. 4 Structure of polycrystalline Silicon solar cell [6]

By applying an external potential difference, it is possible to modify the potential barrier. By applying a positive voltage, the barrier value is lowered, and diffusion phenomena occur. Applying a reverse voltage greatly increases the effect of the potential barrier, and the only current that is produced is that induced by the electric field. It is possible to find a correlation between externally applied voltage and current that can be measured, the current is given by the contribution of two terms, that of diffusion (first term) and that of drift (second term):

$$I = I_0 \cdot e^{\frac{qU}{mkT}} - I_0$$

(1. 4)

I_0 – Saturation Current	It is the current that is generated in the diode when subjected to a negative voltage. therefore due to the effects of the electric field in the junction.
q – Electron charge	1.602×10^{-19} C
U - Tension	Potential difference between the terminals of the diode

m – Quality factor of junction	It is a dimensionless parameter to take into consideration the constructive characteristics of the crystal, for Si it is equal to 2
k – Boltzmann constant	1.380 10^{-23} J/K
T – Absolute temperature	Absolute temperature expressed in K measured on the joint surface.

Table 1. 1 Different terms of current formulation

The photoelectric effect could lead to the movement of electrons from their valence band towards the conduction band. A movement of electrons is then created which takes the name of photovoltaic current:

$$I_{ph} = qNA$$

(1. 5)

Where is it:

- N is the number of photons

- A is the area exposed to radiation

The direction of this current is opposite to that of diffusion since it is oriented by the junction field.

1.3.4 Equivalent circuit

In *Figure 1.5* it is possible to see the equivalent circuit of a solar cell

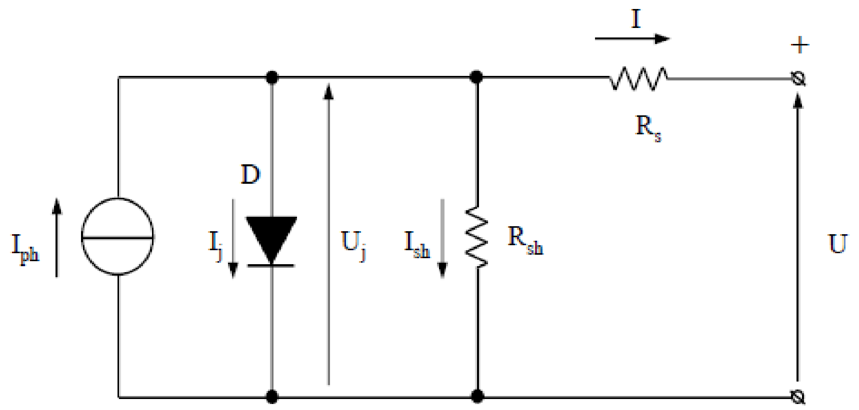

Figure 1. 5 Equivalent circuit of solar cell [6]

In which:

- The photovoltaic current I_{ph} is generated by an ideal current generator.

- I_j is the current flowing through the diode placed in antiparallel with respect to the current generator.

- R_{sh} Shunt resistor is connected in parallel with the current generator and measure the dispersion losses

- R_s Series resistor is connected in series with the current generator and represent the resistances of the electrodes and contacts.

- U is the tension load

- I is the current load

By applying the Kirchhoff's circuit laws to the equivalent circuit just described, it is possible to derive the formulations for the voltage and current at the terminals of the solar cell.

$$I = I_{ph} - I_j - \frac{U_j}{R_{sh}}$$

(1. 6)

$$U = U_j - R_s I$$

(1. 7)

$$U = \frac{mkT}{q} ln\left(\frac{I_{ph} - I\left(1 + \frac{R_s}{R_{sh}}\right) - \frac{U}{R_{sh}} + I_0}{I_0}\right) - R_s I$$

(1. 8)

Figure 1.6 shows the relationship between the current and the voltage at the cell terminals and the relative power calculated as the product of the two terms. To define these characteristic curves, it is appropriate to set the temperature and irradiance, in this case the values refer to the standard conditions.

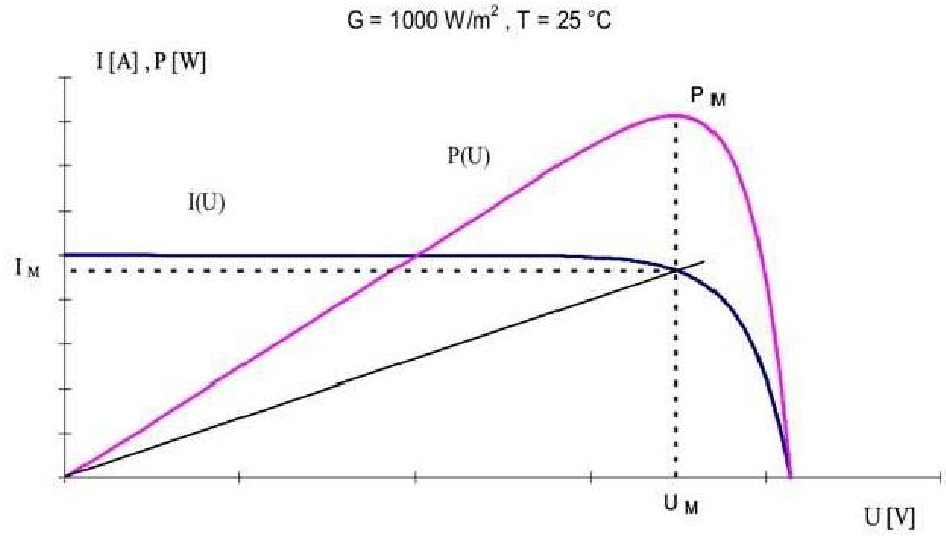

Figure 1. 6 Characteristic curve of solar cell at standard test condition

The characteristic curve shown in *Figure 1.6* refers to the operation of the cell in generator conditions. However, it should be noted that it can also function as a load, working with negative voltages and\or currents, taking care not to exceed the limit conditions of the cell which could cause permanent damage.

Two other points are defined from the characteristic curve of a solar cell: the short-circuit current I_{sc} and the open-circuit voltage U_{oc}. These points refer to two particular operating conditions and are found in the I-U graph between the intersection of the characteristic curve and the system axes.

1.3.5 STC And NOCT

The parameters of the photovoltaic module are calculated with tests carried out in the laboratory; the conditions of these tests are:

- $G = 1000\ W/m^2$

Air mass AM = 1.5. It refers to the spring and autumn weather conditions. The mass of air is a dimensionless parameter that is introduced to take into account the effects of the atmosphere. It is calculated through the solar elevation angle and reaches the minimum value when the sun is vertical with respect to the considered surface (θ_z zenith angle). So, outside the earth's atmosphere AM = 0.

$$AM = \frac{1}{\cos(\theta_z)} = \frac{p\ [Pa]}{p_0[Pa]\sin(\theta_z)} \tag{1. 9}$$

- $T_{PV} = 25$ °C

- I_{sc}, the short-circuit current is the current measured in a circuit where the terminals are joined together

- U_{oc}, open circuit voltage

Under standard conditions, the cell temperature is assumed to be 25 °C. This is a parameter that varies a lot with the irradiance and the ambient temperature, so to correctly calculate the module temperature in different operating conditions, the NOCT method is used. The NOCT (*Normal Operating Cell Temperature*) is a parameter that is provided by the manufacturer, generally varies between 42 and 50 °C and is defined as the temperature that reaches the module at thermal equilibrium when the irradiance is equal to 800 W/m^2 , the ambient temperature is 20 °C and the wind speed is 1 m/s.

$$T_{PV} = T_a + \frac{NOCT - 20\ [°C]}{800\ [\frac{W}{m^2}]} \cdot G\ [\frac{W}{m^2}]$$

(1. 10)

With this method it is assumed that the temperature of the module is a linear function of the irradiance.

1.3.6 Influence on the cell of irradiance and temperature

The performance of a photovoltaic cell depends on many parameters, the main ones being irradiance and temperature. To study the dependence of these two parameters, tests are carried out in which one of the two parameters is kept constant, and it is shown how the I (U) characteristic curve varies as the selected parameter varies, thus obtaining different curves.

Constant T & Variable G

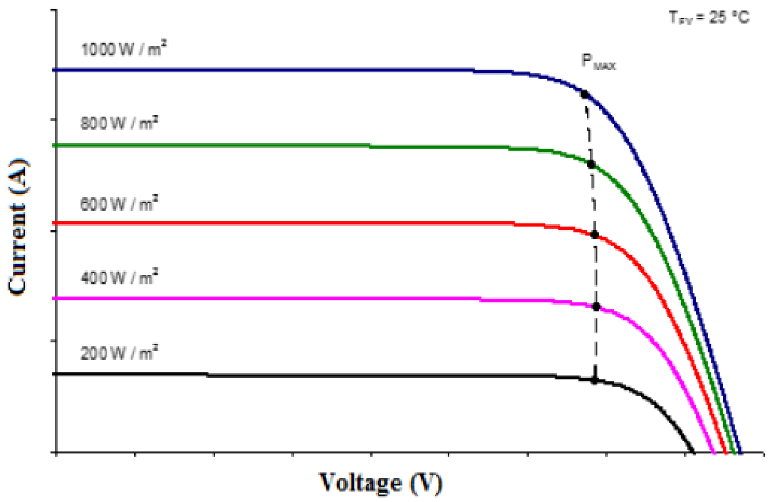

Figure 1. 7 Characteristic curves at different solar radiation [6]

The curve calculated with G = 1000 W/m^2, corresponds to the test carried out in standard conditions, subsequently it is noted that as the irradiance decreases, the short circuit current I_{sc} also decreases significantly, the open circuit voltage U_{oc} decreases but much less evident.

Variable T & Constant G

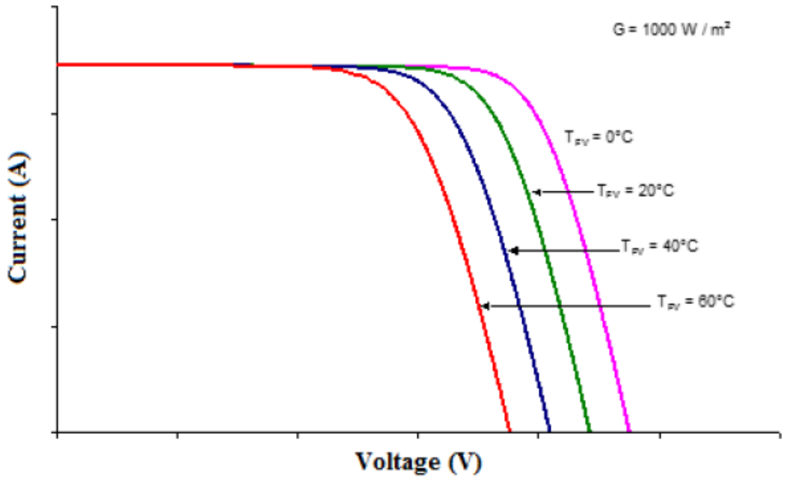

Figure 1. 8 Characteristic curves at different temperature [6]

The short circuit current increases slightly, the open circuit voltage, on the other hand, decreases sharply as the temperature increases, this occurs because with the increase in temperature, diffusion phenomena inside the diode are favoured and therefore the current I_j increases its value and from the Equation 1.7 it can be seen how U_{oc} decreases.

1.3.7 The efficiency of a solar cell

The efficiency of a photovoltaic cell can be defined as the ratio between the maximum power delivered by the cell and the incident solar intensity. Both of these quantities are calculated per unit area.

$$\eta = \frac{P_{MAX}}{G \cdot A} \tag{1. 11}$$

The main causes of a solar cell loss are as follows:

- Reflection: the wave that hits the surface of the module is partially reflected and not completely absorbed (10%).

- Photon energy: only photons with energy equal to the energy gap of the semiconductor are useful. Photons with higher energy will be able to generate a flow of electrons, but excess energy is not used (25%), photons with lower energy are lost completely (20%).

- Recombination: some electron and hole pairs recombine with each other (2%).

1.3.8 Photovoltaic modules

As has already been shown, a photovoltaic cell is formed by a layer of semiconductor material, typically Silicon, and characterized by a certain power. The value of the generated power depends on the current value that it can generate at a given voltage. In current technologies the photovoltaic cell is not used as has just been described, however it is connected to other cells, through copper connections. In this way the photovoltaic module is formed, typically composed by 36, 64, 72 or 96 cells connected to each other, such as to generate a current and a voltage much higher than those of a single cell. The cells that form the module are also very sensitive technologies to various degradation phenomena. For this reason the module is covered with a layer of glass that allows solar radiation to pass, but protects the cells from atmospheric damage, such as rain, snow, dust and humidity, as well as protecting the module from falling hail. The cells are also covered with a layer of Ethylene Vinyl Acetate (EVA) which holds the cells and welds together, creating a compact structure. In the back there is instead a closing panel, typically in Tedlar.

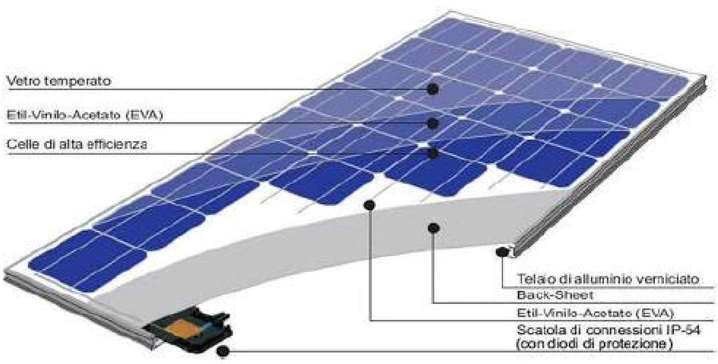

Figure 1. 9 Components of a photovoltaic module [5]

1.3.9 Components of a photovoltaic system and mismatch

The photovoltaic modules are able to produce power in the order of a few hundred Watts. It is therefore necessary to connect several modules together to increase the output power. The connection between modules can take place in series or in parallel. Several modules connected together create a string whose total voltage is equal to:

$$U_{string,max} = \sum U_{OC,i} \tag{1. 12}$$

An array, on the other hand, is a parallel connection between several strings.

Each photovoltaic module is characterized by its characteristic curve. However, there are several factors that cause differences between the various module curves. Among the main ones there are the constructive differences between the modules or the different operating conditions, caused by local phenomena such as shading. The difference between different characteristic curves is called *mismatch* and causes power and efficiency losses.

The mismatch can occur for both series and parallel connections, therefore protection systems are needed to avoid these conditions.

In series connections, if a cell has different characteristics from the others, the voltage is given by the sum of the voltages of each single cell, but the current flowing must be the same, i.e., that of the damaged module.

$$U_{tot,series} = \sum_{i}^{n-cells} U_i \tag{1. 13}$$

$$I_{tot,series} = I_{min} \tag{1. 14}$$

In parallel connections, the case is dual, i.e., the total current is given by the sum of the currents, but the voltage is equal to the voltage of the module in fault.

$$I_{tot,series} = \sum_{i}^{n-cells} I_i$$

(1. 15)

$$U_{tot,series} = U_{min}$$

(1. 16)

The most important protection systems are diodes, which are elements that allow current to flow in one direction only. In the series connection, the bypass diode (D_p), connected in anti-parallel, allows to eliminate the contribution of the worst cell without damaging the performance of the entire connection. For the parallel instead the blocking diode Ds, connected in series to each string, has a dual behaviour. However there is a voltage drop due to its threshold voltage, for this reason it is connected to a very large group of cells in series. so that the threshold voltage is negligible.

1.3.10 Estimation of production

A photovoltaic system is able to produce electricity in direct current and it is possible. Knowing the climatic data of the site to be analysed and the characteristics of the modules to be installed, it is very useful to estimate the productivity of the system.

$$E_{AC} = H_g \cdot S_{PV} \cdot \eta_{STC} \cdot PR$$

(1. 17)

$$E_{AC} = P_N \cdot h_{eq} \cdot PR$$

(1. 18)

In the formulation of Equation 1.17, Hg represents the global in plane irradiance, S_{PV} the area of the photovoltaic generator, η_{STC} the efficiency calculated under standard conditions and PR (Performance Ratio) is a dimensionless parameter that takes into account various causes of losses.

$$PR = \overset{\text{Intrisic mismatich}}{\eta_{mis}} \cdot \underset{\text{dirt and reflection}}{\eta_{d,r}} \cdot \overset{\text{AM} \neq 1{,}5}{\eta_{spect}} \cdot \underset{\text{wiring and blocking diode}}{\eta_{wir}} \cdot \overset{T \neq 25\ {}^{\circ}\text{C}}{\eta_{temp}} \cdot \underset{\text{shading effect}}{\eta_{shad}} \cdot \overset{\text{DC to AC convertion}}{\eta_{PCU}}$$

(1. 19)

This formulation represents the main causes of losses that determine the value of the PR. This parameter varies between 0.55 and 0.85.

In Equation 1.18, the productivity is calculated from the value of the nominal power of the modules in standard conditions and from the value of the equivalent hours. This last parameter is defined as the ratio of daily radiation to irradiance and indicates the number of hours in which the system works at nominal power in a given time interval.

1.3.11 State of art and future

Among the semiconductors used for photovoltaic cells, monocrystalline silicon is the most widespread element. This element is very difficult to find in nature in pure form. In fact, it is extracted through various chemical processes from Silicon Oxide. Polycrystalline silicon, on the other hand, is obtained from waste components of electronic equipment. The amorphous one, on the other hand, does not have a crystalline structure, like the first two. In this case some silicon atoms bind to hydrogen atoms. The cost of modules made with this material are lower than those made with crystalline structures.

Other PV cells are instead made of Indium-Copper-Diselenide (CIS) and Indium-Copper-Gallium-Diselenide (CGIS), they are made by overlapping different materials. In this way, the solar spectrum is more exploited, using materials capable of capturing electromagnetic radiation at different wavelengths, thus reducing the energy lost by unusable photons.

Among the most economically convenient modules on the market are the one formed by Cadmium-Tellide (CdTE), as the materials used derive from waste from other industrial processes. Among the modules with the highest efficiency, even higher than 30%, there are those formed by gallium arsenide (GaAs); however, the cost of these modules is not suitable for commercial use.

Among the innovations of this technology, there are the organic cells. This system is formed by mater polymeric materials, in this way it is possible to realize structures at a reduced cost. A further advantage is that of presenting different colours (and not just black) in order to be used more easily in architectural applications. The flaw of this technology is the still reduced performance compared to commercial competitors. Other innovations, on the other hand, still concern Silicon, this time used in structures and thin films, with reduced thicknesses compared to traditional cells, also managing to generate higher power.

1.3.12 Connection with the load

Unlike traditional electricity generators, in photovoltaic generators, it is impossible to regulate the input power, the power control is much more complicated. For this reason, in systems of this kind, it is the load that adapts to the generator. Based on the irradiance and temperature conditions, in the characterization curve of the photovoltaic system, it is possible to find the maximum power output in those conditions.

1.3.13 Inverter

A photovoltaic system is capable of generating electricity in direct current, but most of the final loads require alternating current. Furthermore, for connection to the distribution grid it is necessary that the electric current is alternating and that it complies with certain technical standards. For this it is necessary to use a DC\AC converter, the Inverter. Through this system it is possible to generate alternating electric current at 50 Hz (for systems installed in Europe). The switching process takes place through switches and diodes connected in antiparallel. The switches can be of the Mosfet or IGBT type and their movement is activated with a certain frequency, called the switching frequency, which is generated thanks to the PWM (*Pulse Width Modulation*) technique, by comparing a sine wave with the same frequency as the wave to be generated, with a bipolar triangular wave, thus generating a square wave which regulates the switches.

The *Figure 1.10* shows a diagram of an inverter, and the *Figure 1.11* shows the PWM comparison technique, with which the switching signal is generated.

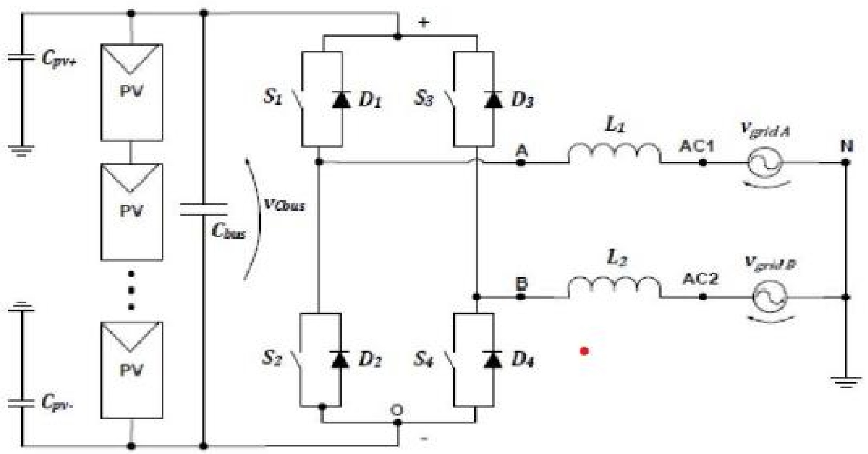

Figure 1. 10 Diagram of a full bridge inverter

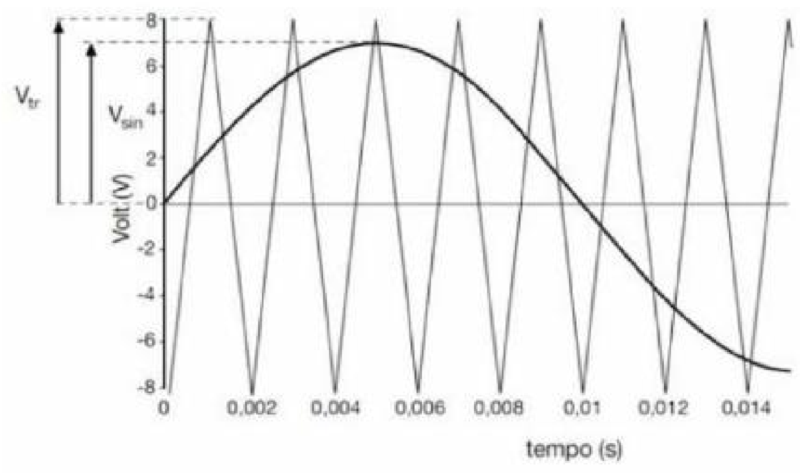

Figure 1. 11 Pulse Width Modulation technique - comparison between a sine wave and a triangle wave

The information, equations and figures in this paragraph on photovoltaic system summarize the information contained in documents [5] [7] [6], [8] and [9].

1.4 General aspect of WT

Wind Turbines (WT) are systems in which it is possible to convert the kinetic energy of the wind into electrical energy. Wind energy is considered a renewable source as it is inexhaustible, moreover, no type of pollutant is produced for the air during operation. Through these systems it is possible to produce energy in remote areas without the use of fossil fuels. The main disadvantages of this technology are related to the uncertainty of the wind, and the difficult forecast of the source. Other disadvantages are represented by the visual impact and noise pollution that limit the installation of these systems.

1.4.1 Characterization of the wind source

The solar radiation that affects the Earth is not perfectly balanced, thus creating warmer areas, near the equator, and colder areas at the poles. The Earth also moves around the Sun and spins on its fixed axis. These mechanisms cause the movement of large masses of air that move from one part of the Earth to another. In addition to these phenomena, other effects must also be considered, such as a pressure difference between the areas considered and the Coriolis effect. It is possible to exploit the movement of these masses of air to generate electricity.

Local effects modify the propagation of the wind. Among these are, the roughness of the surface, the elevation of the ground and the presence of obstacles such as buildings or trees.

The measurement of wind speed and its direction takes place through anemometers. These systems exploit different technologies to provide the necessary information at a given height. To take into account some local effects, including the roughness of the ground, it is possible to use Equation 1.20. This formulation allows to evaluate the wind speed at a different height from the reference one considering the effects of roughness.

$$u(h, Z_0) = u_{ref} \frac{\ln\left(\frac{h}{Z_0}\right)}{\ln\left(\frac{h_{ref}}{Z_0}\right)} \tag{1. 20}$$

Wind speed data for the analysed site are grouped and analysed as probability density. The Weibull distribution function approximates very well this trend (Eq. 1.21)

$$f(u) = \frac{k}{u}\left(\frac{u}{c}\right)^{k-1} e^{-\left(\frac{u}{c}\right)^{k}}$$

(1. 21)

Where “k” represents the shape factor and “c” the scale factor. In this way it is possible to obtain the annual wind speeds for the analysed site, using only two parameters. These parameters are calculated from the mean wind speed values and the standard deviation.

This function expresses the probability that the wind has a certain speed range in a year, it is therefore expressed as a percentage with respect to the 8760 hours per year.

Wind turbines use wind energy to produce electricity. In fact, they convert the kinetic energy of the wind into mechanical energy of the rotor and subsequently through a motor the energy is converted into electrical energy.

The power of the wind depends on the speed and density, as indicated in Equation 1. 22

$$P = \frac{1}{2}\rho A U^3$$

(1. 22)

Where A represents the rotor area.

In current technologies it is impossible to convert all the wind power, due to physical and technological limitations. Many theories provide information on the power that the wind rotor can generate. Therefore, dimensionless parameters are provided which include the various causes of losses and which reduce the maximum extractable power.

Betz's theory indicates the maximum power that can be extracted from the wind by an ideal turbine. According to this theory, the wind speed is undisturbed and two-dimensional, the rotor is formed by an infinite number of blades, the density of air is constant, and no rotational waves are formed. The dimensionless coefficient calculated according to this theory is approximately equal to $C_{p,\,max} = 0.59$.

$$P = \mathrm{Cp} \cdot \frac{1}{2} \rho A U^3 \tag{1. 23}$$

In reality the power coefficient is lower than this value.

Wind turbine manufacturers will have to provide power curves for each generator. The power curves are graphs in which the extractable power from the turbine at different wind speeds is indicated. *Figure 1.12* shows an example of a power curve.

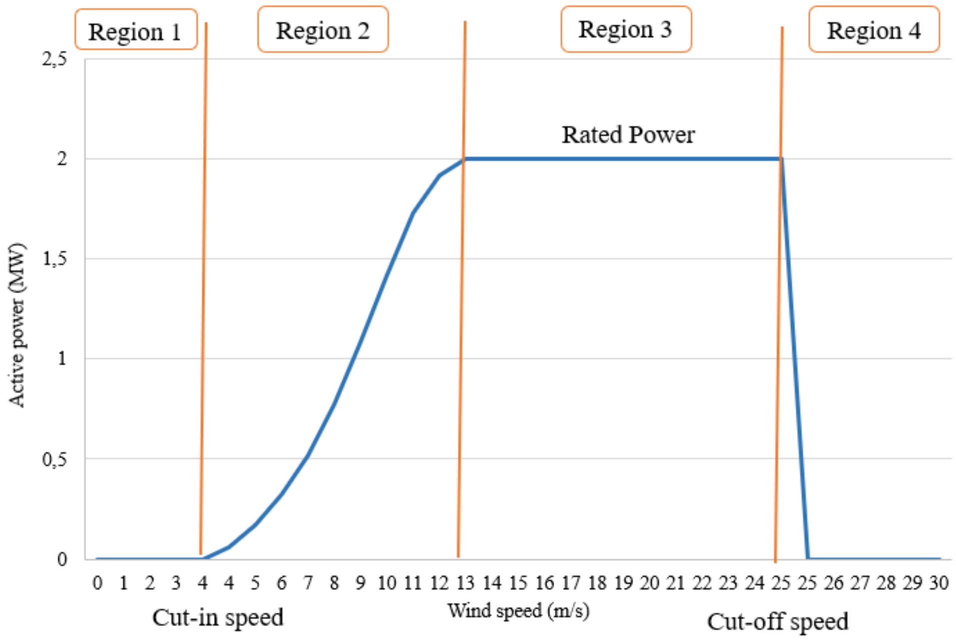

Figure 1. 12 Power curve of wind turbine

As can be seen in regions 1 and 4 the turbine is unable to power because the wind speed is too low in the first region, and too high in the fourth. In the latter case, the turbine could be subject to structural problems, and it is therefore preferable to activate the safety systems. In region 2 there is an increase in the power generated with increasing wind speed. On the other hand, in region 3 the power is kept constant.

1.4.2 Calculation of energy production

The productivity of a turbine is given by the sum of the products of the frequency distribution of the wind and the power curve of the generator. Using the probability distribution, the hours present in a year must be considered and speeds lower than the cut-in speed and higher than the turbine cut-off speeds are excluded from the calculation, for the reasons highlighted above.

$$E_{AC}(kWh) = 8760 \sum_{u=u_{cut-in}}^{u=u_{cut-off}} (P_{el}(u) \cdot f(u))$$

(1. 24)

Figure 1.13 represents an example of the two curves taken into consideration.

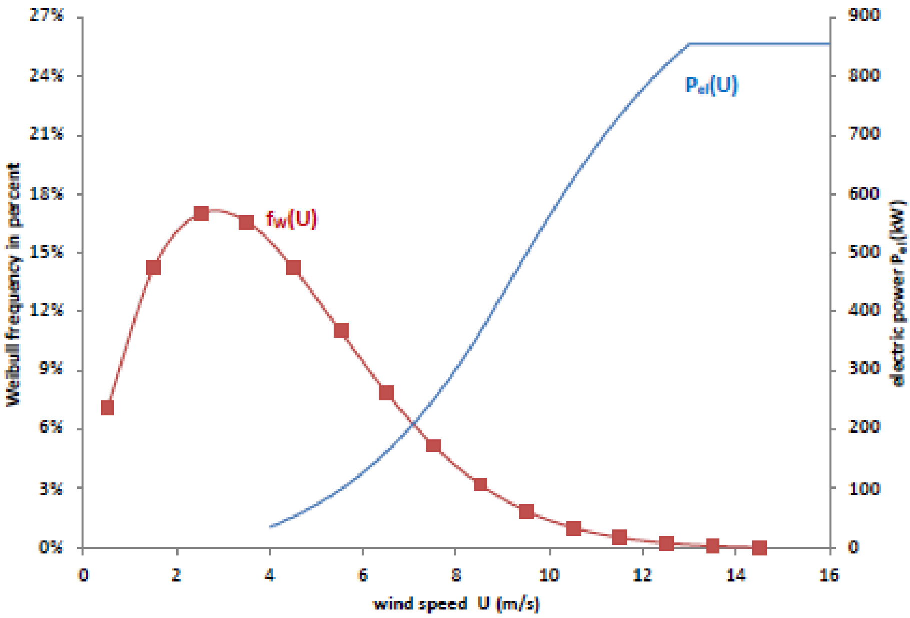

Figure 1. 13 Power curve of WT and Weibull distribution [10]

The calculation of the productivity takes place for the value of the wind speed expressed at the height of the hub.

1.4.3 Wind turbine components

Inside a wind turbine there must be a system capable of converting the mechanical energy of the blades into electrical energy. The first mechanism present in many commercial turbines is the gearbox, capable of increasing the rotation speed from 5-30 rpm up to over 1000 rpm. Then there is a motor capable of converting mechanical energy into electrical energy. Furthermore, inside the turbine there are also other systems capable of regulating the performance of the turbine itself. For example, the adjustment system capable of adjusting the rotor axis based on the speed and direction of the wind. And the braking system can control the most dangerous and extreme conditions and eventually stop the system. *Figure 1.14* shows the main components found inside a generator. In particular, there are two different technologies for the electromechanical generator, the fixed speed, and the variable speed one. The latter is the most used on the market, around 60%. Among this technology, the DFIG (*Doubly Fed Induction Generator*) is the most used because it allows the turbine to be used in a wider range of wind speed.

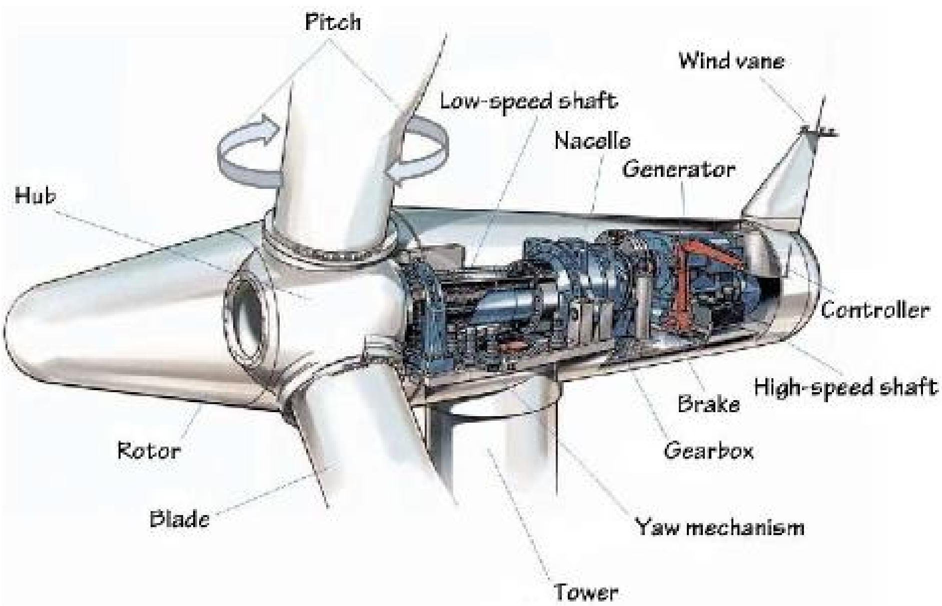

Figure 1. 14 Components of a wind turbine [10]

1.4.4 Wind turbine classification & offshore technology

According to the IEC 61400-1 standard, turbines are divided into 7 categories based on the mean speed measured at the hub, the standard deviation and two other parameters that take into account the extreme speeds measured.

In recent history, more and more attention are being paid to offshore wind turbine installations. With this configuration it is possible to create large-scale wind farms, moreover the production is higher than the onshore installation because the propagation of the wind is almost undisturbed. Furthermore, with this type of installation, the effects due to noise pollution and landscape constraints are reduced. However, installation and maintenance costs increase. In 2018, 2.4% of the electricity in the European Union was produced by this type of offshore technology. The installation of offshore wind turbines can be performed with two different techniques, bottom fixed and floating ones. The latter are mainly used when the sea depth is greater than 50 m.

The information, equations and figures in this paragraph on wind turbines summarize the information contained in documents [6], [10] and [11]

1.5 Electrochemical storage systems

The electrochemical storage systems allow to store electrical energy with high efficiency, about 70-80%. This kind of technology is mainly used for electric vehicles and renewable energy production systems. The main disadvantage of these systems are the high cost of installation and the poor ability to store large amounts of energy. To characterize the batteries, one of the main parameters is the Capacity. It is defined as the amount of energy that can be stored and is measured in [Ah]. Another very important parameter is the number of cycles, i.e., the number of charges and discharges that can be performed. For batteries connected to renewable plants, this is a important parameter for the useful life of the batteries; in fact, there are several activations of the system to guarantee the satisfaction of the load continuously.

1.5.1 Principle of operation

Electrochemical cells are systems in which direct conversion from chemical energy to electrical energy take place and vice versa.

The main components of an electrochemical cell are the two electrodes, an electrolyte and a conductor for the flow of electrons. Batteries are a type of electrochemical cells, in which the two electrodes are called Anode and Cathode.

In one electrode the oxidation reaction takes place and electrons are released, at the other electrode reduction processes take place and occurs when the electrons are recombined with ions. The electrolyte material, placed between the two electrodes, allows the passage of ions between the two electrodes and limits the passage of electrons. Instead, electrons move through an external conductor. Through these processes there is a flow of electrons (current) passing from an external conductor and a potential difference for the oxidation and reduction processes occurring at the electrodes.

Figure 1.15 show representative diagram of the charging and discharging process of a battery. The two processes are dual. During the discharge phase, it is possible to supply an external load, while in the charging process the process must be activated by an external source to active the reverse reactions. Through this mechanism it is possible to charge the battery when there is a surplus of electricity, store it in the battery for a certain period and discharge the battery when there is an external need of energy. The energy is then stored in the form of chemical energy inside the battery.

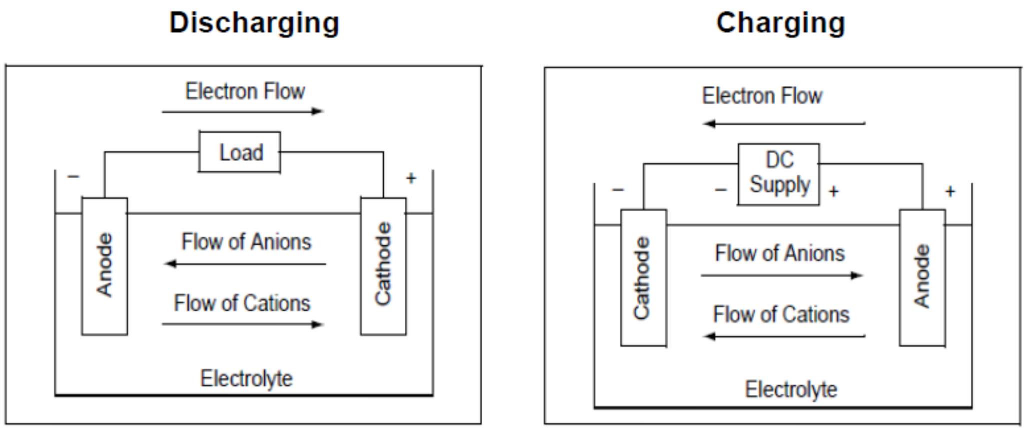

Figure 1. 15 Charging and discharging processes of a battery [12]

1.5.2 Different battery technologies

There are different types of batteries used, which differ in the type of materials used and performance.

Lead-acid battery

Whole reaction:

$$Pb + PbO_2 + 2H_2SO_4 \leftrightarrow 2PbSO_4 + H_2O \tag{1. 25}$$

In this configuration, the anode is made up of Lead and the cathode of Lead oxide, as shown in *Figure 1.16*.

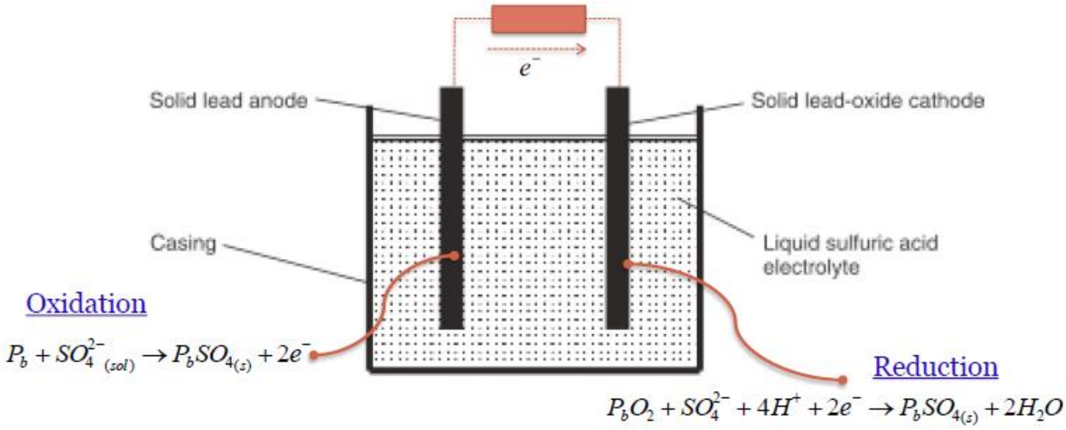

Figure 1. 16 Representation of an acid lead battery [13]

This kind of technology is the most used in the market for their performance and low costs. However, the useful life is reduced and a low energy density and requires large dimensions to be used on an industrial level.

Li-ion battery

Whole reaction:

$$Li_{1-x}CoO_2 + C_6Li_x \leftrightarrow LiCoO_2 + 6C \tag{1. 26}$$

It has a high specific power, and very fast charge and discharge times. However, it exhibits dangerous performance when subjected to high electrical or thermal overloads.

Table 1.2 summarizes the main information for the major types of batteries used on the market.

	Specific Energy [Wh/kg]	Energy Density [Wh/L]	Life cycle	Specific power [W/kg]
Lead Acid	20-35	54-95	≤800	250
Ni-Cd	40-50	70-90	≤1200	220
Ni-MH	70-95	150	≤1000	200-300
Li-ion	150			420

Table 1. 2 Main data of batteries in the market

As previously described, lithium-ion batteries have a higher specific energy than lead acid batteries, creating more compact and lightweight systems, useful for different applications.

The information, equations and figures in this paragraph on wind turbines summarize the information contained in documents [6], [12] and [13].

1.6 Introduction to RES_tool

In this thesis work, the "RES_tool" program is used to perform the planning analysis and obtain estimates of the main indicators used for the energy and economic analyses. The program is implemented within the Excel software. It is composed of several spreadsheets in which the models of the photovoltaic and wind systems are implemented, as will be described in the following paragraphs, and through which it is possible to obtain the estimates of some key parameters in the planning phase of new RES projects. *Figure 1.17* represents, in a simplified way, the functions performed by the program. In this representation, the RES_tool program is represented as a "black-box", in which the meteorological data, the electrical load, and the economic and energy data of the system are in input and through which it is possible to obtain the main parameters useful for planning analysis.

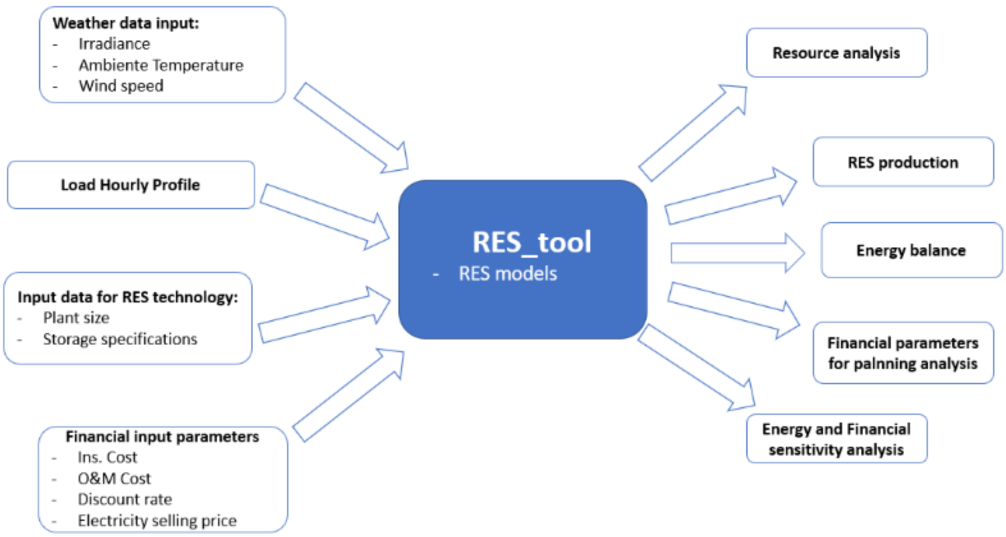

Figure 1. 17 Representation scheme of the RES_tool program

For the calculation of the various parameters it is essential to import the meteorological data on an hourly basis for each selected site. Meteorological data are obtained from the PVGIS website [14]. It is possible to import this data by running a macro capable of copying the data downloaded from the site within the program.

From the PVGIS database, for each selected site, the following data is downloaded:

- The irradiance expressed in kW/m^2 on the surface, in this case it is possible to select the data by varying the Azimuth and the angle of inclination.

- The ambient temperature of the external air °C.

- The mean wind speed m/s referred to 10 m height.

The data provided refer to the period between 2005 and 2016. In this way it is possible to analyse, in addition to a daily and seasonal variation, also an annual variation of the various data, in order to analyse how the resources varies between the different years taken into account.

In the model of wind and photovoltaic systems it was assumed that the useful life of the plant is equal to 25 years. To perform the analysis over such an extended period it is necessary to replicate twice the downloaded data referring to 12 years, with the exception of the year 2005, which is repeated three times. To perform the analysis correctly, in addition to the meteorological data, it is necessary to import the data relating to the electrical load for the analysed site into the "RES_tool" program, which are important for calculating self-sufficiency and self-consumption parameters. To calculate the hourly load, it is possible to import the annual hourly load referring to a single year and set the annual percentage growth coefficients. The program will be able to create an hourly profile for 25 years, with the selected increment.

After importing the meteorological data, the imported data can be analysed in a representative manner within the program. “Heat maps” are created, which summarize the monthly average data for each year of temperature, irradiance and wind mean speed. The data of the standard deviation, of the variance, the mean value and the median of the represented data are also automatically calculated. Through these tables, it is simple to have the distribution of the quantities taken into consideration, and to perform an analysis of the resources for the suitable site.

Within the RES_tool, the RES models are implemented to represent the operating principle of these technologies. Within the program it is possible to select the sizes of the generators and the capacity of the storage batteries. By selecting the parameters, the program is able to calculate the productivity of the plants, the exchanges with the grid and the value of self-consumption and self-sufficiency. It is also possible to define the economic parameters for the plants treated, which will be used by the program for the calculation of the economic parameters will be described in Paragraph 3.2.

The analysis just described is initially performed for a single reference year, after which the simulations can be performed over a period of 25 years.

One of the main features of this program is the possibility of carrying out a sensitivity analysis on the project under consideration. The sensitivity analysis can be conducted on both energy and economic parameters. It is possible to note how the characteristic parameters vary with the variation of an input data.

The energy data that can be changed include:

PV system	**WT system**	**Storage system**
Plant size	Plant size	Storage capacity
		Max and min state of charge
		Limit in power
		Charge and discharge efficiency
		Max number of cycle and max lifetime

Table 1. 3 Energy data that is possible to change for sensitivity analysis

Among the financial data are:

PV system	**WT system**	**Storage system**
Installation cost	Installation cost	Installation cost
O&M cost	O&M cost	
Discount rate	Discount rate	
Electricity selling price	Electricity selling price	

Table 1. 4 Financial data that is possible to change for sensitivity analysis

The RES_tool program is also able to carry out an environmental analysis of the project. For each resource a coefficient is assigned, this coefficient represents the quantity of CO_2 emitted into the environment for each kWh of electricity produced. Through these, it is possible to calculate the quantity of CO_2 released into the environment and allows to make an estimate of the reduction of CO_2 introduced using renewable energy systems compared to traditional systems.

1.7 RES Models

In the previous paragraphs the fundamental aspects of photovoltaic, wind and electrochemical storage systems were described. This paragraph describes how these technologies are modelled within the RES_tool program and the fundamental parameters that characterize these technologies.

It was assumed that the selected generators, photovoltaic and wind power system, are connected to a single direct current (DC) node. The battery is also connected to the same node, as shown in *Figure 1.18*.

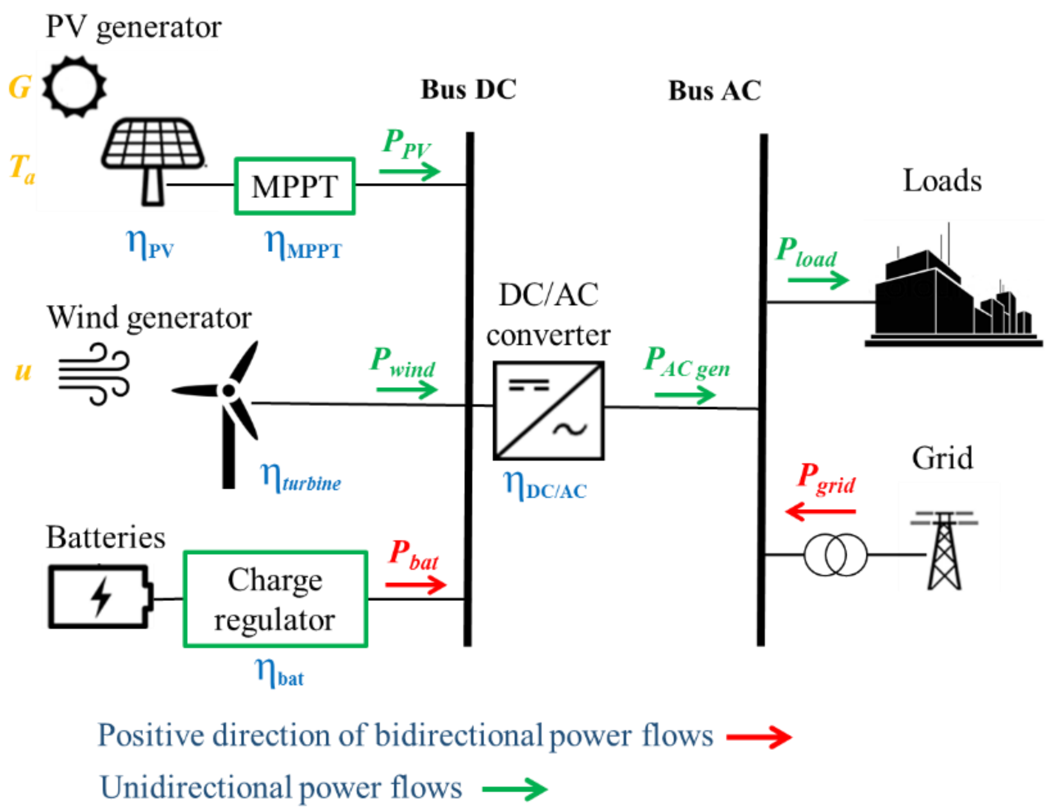

Figure 1. 18 Representative diagram of generation system used [15]

The load is instead represented by the final users and the grid to which the generators are connected and they work in alternate current (AC). For simplicity of analysis, the alternate current node are also connected to a single direct current node. Between the two nodes there is therefore the need to install a converter capable of transforming DC into AC. It was also assumed that the inverter is unidirectional, therefore it is not possible to draw energy from the grid to charge the batteries. The inverter will be sized considering the power of the photovoltaic and wind generators, while the battery will only be in operation when there is no energy production by renewable energy generators.

1.7.1 Photovoltaic model

The formulas described below were used to model a photovoltaic system in RES_tool programme. Using the climatic data, it is possible to estimate the energy produced by these generators, through the use of some parameters that take into consideration the real conditions of use and operation of these systems.

$$P_{DC} = P_{PV} \cdot \frac{G}{G_{STC}} \eta_{mix} \eta_{th} \tag{1. 27}$$

$$\eta_{th} = 1 + \gamma_{th} \cdot (T_m - T_{STC}) \tag{1. 28}$$

$$\eta_{mix} = \eta_{dirt} \cdot \eta_{refle} \cdot \eta_{mis} \cdot \eta_{cable} \cdot \eta_{MPPT} \cdot \eta_{shade} \tag{1. 29}$$

$$T_c = T_{air} \cdot \frac{NOCT - 20\ [°C]}{G_{NOCT}} \cdot G \tag{1. 30}$$

$$T_c = 0.943 \cdot T_a + 0.028 \cdot G - 1.528 \cdot u_{wind} + 4.3\ [°C] \tag{1. 31}$$

For the calculation of the electric power in direct current (Eq. 1.27) the peak nominal power P_{PV} measured in standard conditions (G_{STC} = 1 kW/m^2) and T_{STC} =

25 °C) is used. To take into account the effects of irradiance in the power calculation, the G/G_{STC} ratio is used.

Losses are divided into two categories, those that depend on temperature (Eq. 1.28) and those independent of temperature (Eq. 1.29).

As described above, the simulations will be performed on an hourly basis, the power extracted from the generator will therefore vary with the climatic conditions of the time analysed, which will change in irradiance and temperatures.

As shown in *Paragraph 1.3*, the performance of the PV modules is affected by temperature, in particular as the temperature of the cell increases, the efficiency of the module is reduced. It is necessary to correctly estimate the temperature of the cell, for this reason the NOCT model (Eq. 1.30) is used. Through this method, the Tc temperature is calculated, using the irradiance and ambient temperature data of the analysed site obtained from PVGIS. Using this formulation it is necessary to define the NOCT value, which varies according to the type of installation and is provided in the technical data sheets of the modules. In this analysis, a value of 45 °C was used for systems installed on the ground and a value of 47-48 °C for systems installed on buildings. Within the RES_tool program it is possible to calculate the cell temperature with a other method. This method is called Wind effect, in this case, a semi-empirical formula is used to calculate the temperature of the cell Tc, as a function of the wind speed. As the wind speed increases, there is a reduction in the cell temperature, with the same irradiance and ambient temperature since the phenomena of convective heat exchange are favoured. In this work the NOCT model was used, however, it was noted with the two models the solutions found are very similar.

Table 1.10 summarizes all the data used for the photovoltaic generator model and for the production calculation

$$P_{DC} = P_{PV} \cdot \frac{G}{G_{STC}} \eta_{mix} \eta_{th}$$

$$\eta_{mix} = \eta_{dirt} \cdot \eta_{refle} \cdot \eta_{mis} \cdot \eta_{cable} \cdot \eta_{MPPT} \cdot \eta_{shade}$$

Symbol	Value	Description
η_{dirt}	0.98	For the presence of dust or other materials on the glass surface. This value is lower for modules with low inclination.
η_{refle}	0.97	Losses due to the inevitable reflection phenomena that occur on the glass of the PV module
η_{mis}	0.97	These losses are caused by the mismatch phenomena that occur when modules with different characteristic curves are connected together
η_{cable}	0.99	Caused by the dissipation of energy due to Joule effect phenomena due to the passage of current through the material of the cables $P_{diss} = R \cdot I^2$
η_{shade}	0.99	These losses depend on external causes to the generator and depend on the presence of overhangs that could reduce the solar radiation that affects the PV module.
γ_{th}	-0.005 [1/°C]	Thermal coefficient for calculation over temperature losses
G_{lim}	0.0177 [kW/m^2]	When the solar irradiance is not higher than this limit value it is impossible to activate the inverter and therefore there is no electricity generation.

Table 1. 5 Data used for modelling the photovoltaic system

The PV modules used in this study are fixed axis. A useful life of the plant of 25 years is considered, to take into account the effects of degradation on the plant, a correction coefficient of 0.5% per year is used, which reduces the efficiency of the system.

1.7.2 Wind turbine model

The modelling of this technology is performed through the Equations 1.32 and 1.33

$$P_{mec} = \frac{1}{2} \cdot \rho \cdot A \cdot U^3 \cdot C_p(\lambda, \beta)$$

(1. 32)

$$u(h, Z_0) = u_{ref} \frac{\ln\left(\frac{h}{Z_0}\right)}{\ln\left(\frac{h_{ref}}{Z_0}\right)}$$

(1. 33)

With Equation 1.32 is possible to calculate the direct current electrical power generated by the wind turbine. However, this parameter is strongly dependent on the power coefficient which is a function of the tip speed ratio (λ) and on the inclination of the blades (β). This parameter is often calculated from experimental tests on the generator.

The power curve provided by the manufacturer of each wind turbine is used to calculate the productivity, in which the active power generated by the turbine is related to varying wind speed at hub height. In these curves the value of the power coefficient is included in the data provided by the manufacturer.

Within the RES_tool program there are the power curves of 11 different turbines. *Figure 1.18* shows the curves of some of the turbines present. The turbines selected are of the horizontal axis type.

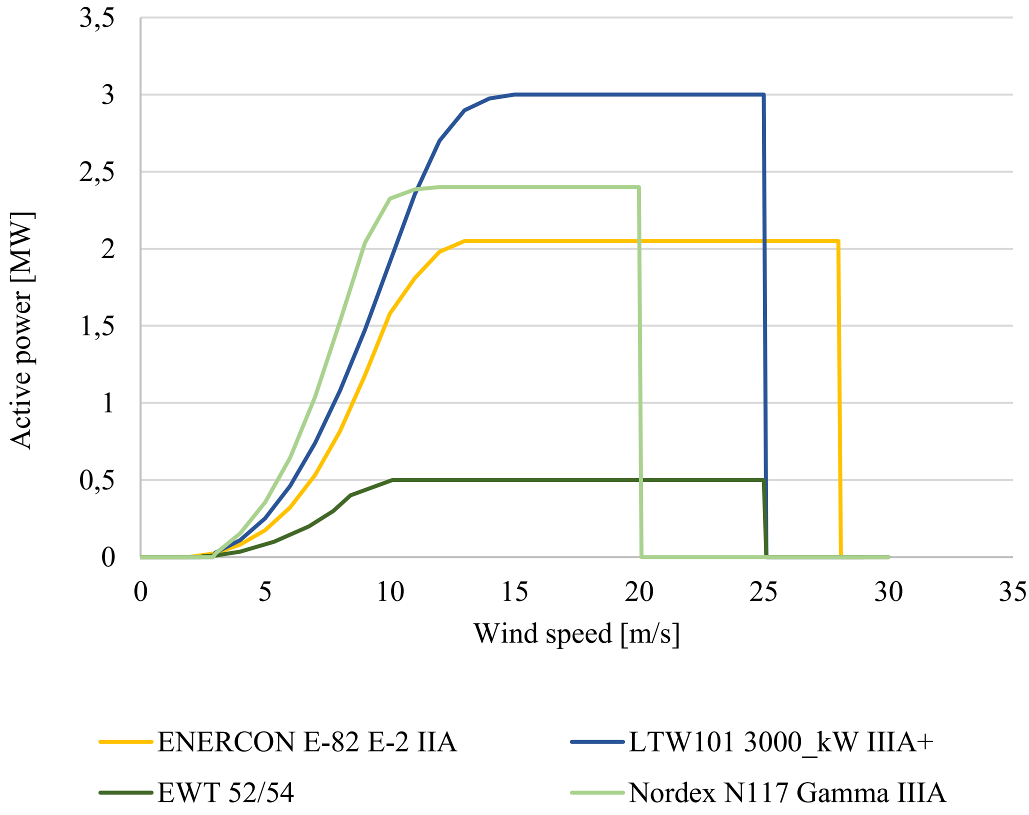

Figure 1. 19 Power curve of four wind turbines

As also expressed in *Paragraph 1.4*, within the power curve, four different areas with different operating speeds can be distinguished. From *Figure 1.18* it is evident how the active power of the turbine is equal to zero when the wind speed is higher than the cut-off speed. However it is evident that different turbines have different operating ranges and can therefore operate in different conditions. The curves shown in *Figure 1.18* are obtained through linear interpolation from the data provided by the manufacturers.

The meteorological data obtained from the PVGIS site refer to 10 m height. The data provided by the manufacturer on the performance of the generator refer to the height of the hub, therefore there is a need to obtain the meteorological data referring to the height of the hub in order to use the power curves correctly. Equation 1.33 is used for this purpose. In this thesis a value equal to 0.15 m was selected as the roughness length

The calculation of the productivity of a wind turbine is performed through the data obtained from the power curve and those of the wind distribution during the year. The Weibull distribution was not used in this study, however, the distribution was calculated experimentally. From the PVGIS site, it is possible to obtain the hourly data of the wind speed, they are subsequently in a Cartesian axis system in which the value of the wind speed and the number of hours in a year in which this value is measured, are reported. The separation range between one speed value and the next is 0.5 m/s. In this way, the speed distribution for one year is obtained, *Figure 1.20* shows a graph of the speed distribution obtained with this procedure and the power curve of a reference turbine. Through this process it is possible to calculate the productivity by adding the values obtained on an hourly basis.

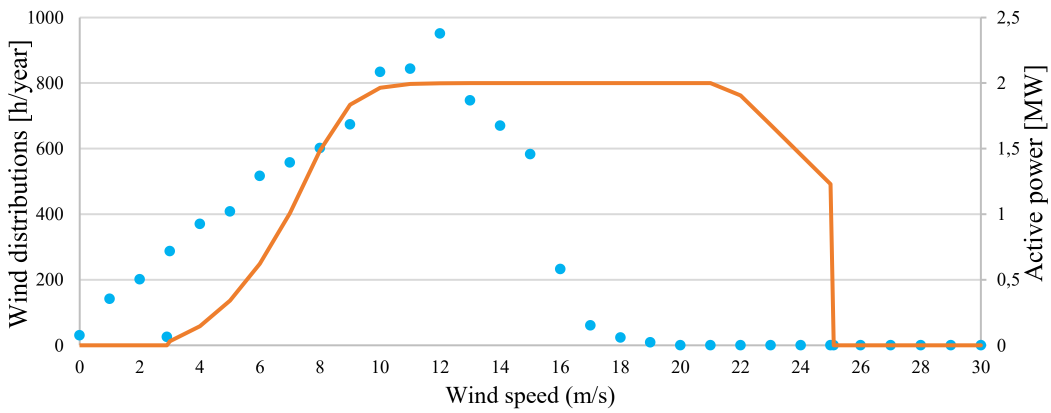

Figure 1. 20 Distribution curve vs. power curve

A useful life of the plant of 25 years is considered, to take into account the effects of degradation on the plant, a correction coefficient of 0.5% per year is used, which reduces the efficiency of the system.

1.7.3 Model of the electrochemical storage in RES_tool

The main indicators to represent the characteristics of an electrochemical storage are its capacity ($C_{storage}$) and the state of charge (SOC). The capacity is defined by the product data sheets. Within the RES_tool program it is possible to modify this parameter based on the size of the generators to which the storage is to be connected. It is possible to select the maximum number of cycles that can be performed and the average life of the battery before being replaced. In this thesis it is assumed that the storage system is replaced every 10 years and that the maximum number of cycles for each battery is 10000 cycles. To model the storage system correctly it is necessary to define the state of charge, it is defined by equations 1.34 and 1.35:

$$SOC(t) = SOC(t-1) + \left(\frac{|P_{bat}| \cdot \Delta t}{V_{bat} \cdot C_{bat} \cdot \eta_{bat,c}} \right)$$

(1. 34)

$$SOC(t) = SOC(t-1) - \eta_{bat,d} \cdot \left(\frac{|P_{bat}| \cdot \Delta t}{V_{bat} \cdot C_{bat}} \right)$$

(1. 35)

By calculating this parameter it is possible to define the percentage of battery charge and thus allows to know the amount of energy that is still available, and how much of this energy can be discharged or charged.

Equation 1.34 refers to the state of charge of the battery, equation 1.35 instead to discharge. The two operating conditions have different efficiencies.

The SOC changes over time and with the operation of the system. It is important to define the maximum and minimum value of this value. In this work, SOC_{min} equal to 20% and SOC_{max} equal to 100% were selected. Exceeding these constraints reduces system performance and could lead to device damage.

The SOC (t) value is a function of its value calculated at the previous instant of time, it also depends on its charging and\or discharging efficiency and the nominal energy value. As can be seen from equations 1.34 and 1.35, SOC depends also, on the product of the average power input or absorbed in a given instant of time and the instant of time considered.

The program progressively calculates the number of cycles performed and the battery life which will be compared with the maximum admissible values.

Table 1.6 shows the parameters used in modelling electrochemical storage systems

$SOC(t) = SOC(t-1) + \left(\frac{\lvert P_{bat}\rvert * \Delta t}{V_{bat} * C_{bat} * \eta_{bat,c}}\right)$		$SOC(t) = SOC(t-1) - \eta_{bat,d} * \left(\frac{\lvert P_{bat}\rvert * \Delta t}{V_{bat} * C_{bat}}\right)$
Quantity	**Value**	**Description**
Total capacity of storage	*Selected value [MWh]	The capacity indicates how much electric current the battery is able to supply in a given instant of time
SOC_{min}	20%	This value refers to the nominal battery capacity and is expressed as a percentage. The battery must not be discharged if it reaches the minimum value.
SOC_{max}	100%	It is impossible to charge the battery beyond its maximum storage limit
$\eta_{discharge}$	100%	In this case an ideal discharge process is assumed, in reality this value is different from 100%
η_{charge}	90%	Not all energy is stored perfectly and a certain amount is dissipated during the process for example as heat
Max number of cycle	10000	Maximum number of charge – discharge cycles from the datasheet
Maximum lifetime	10 years	Maximum number of the years from the datasheet of the storage

Table 1. 6 Parameters used for modelling the electrochemical storage system

1.7.4 DC - AC converter model

The operating principle of the DC \ AC converter was analysed in *Paragraph 1.3.13*. The technology analysed was the inverter. In this paragraph is describe how this technology is modelled.

Equations 1.36 and 1.37 represent, respectively, the conversion efficiency and losses.

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} = \frac{P_{DC} - P_{loss}}{P_{DC}}$$

(1. 36)

$$P_{loss} = P_0 + C_L \cdot P_{DC} + C_Q P_{DC}^2$$

(1. 37)

Efficiency is the ratio between the AC output power and the DC input power. Losses are calculated as through a semi-empirical formulation. The P_0 value corresponds to the standby losses, i.e. the losses that occur even when the conversion process is not in progress. The other two terms are instead a function of the DC power input. The coefficients C_L and C_Q correspond respectively to the linear and quadratic losses due to the presence of diodes and resistive components.

Chapter 2

2 RES installation in Sri Lanka: constraints and suitable sites

Sri Lanka is a South Asian Island surrounded by the Indian Ocean. In 1948 it gained independence from the British Empire and in 1972 was established the Independent Socialist Republic of Sri Lanka. The administrative and legislative capital is Sri Jayawardenapura Kotte. Over the course of recent history, the country has experienced several internal civil wars and natural disasters such as the tsunami in 2004. Currently the state is made up of 9 provinces and 25 districts.

According to data reported by the European Commission, Sri Lanka has put an end to the country's extreme poverty, however the country still suffers from the problems caused by civil wars, which is why the country's economic growth has still slowed down [16].

2.1 Energy context

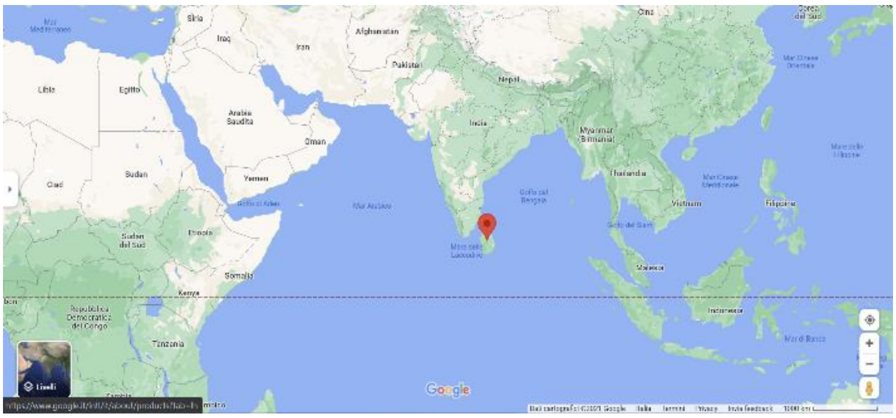

Figure 2. 1 Geographic position of Sri Lanka [17]

Due to its geographical position, being close to the equator, the country has enormous potential of renewable energy, such as wind and solar photovoltaics. An estimate of the potential of this country can be seen in *Figure 2.2* [18].

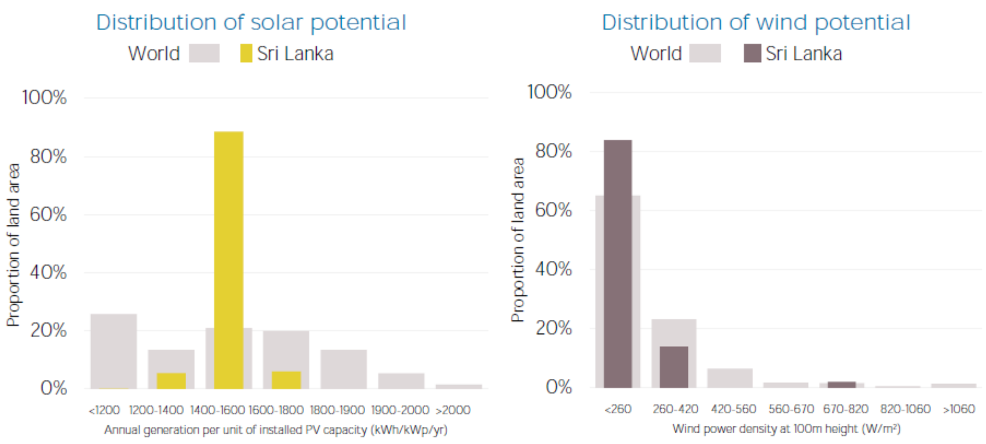

Figure 2. 2 Sri Lanka energy potential [18]

However, despite its large energy resources, the country is heavily dependent on coal and oil, which is mainly imported from foreign countries. From *Figure 2.3* [19] it can be seen how the consumption of electricity over the years has increased significantly, reaching 14.9 TWh in 2019.

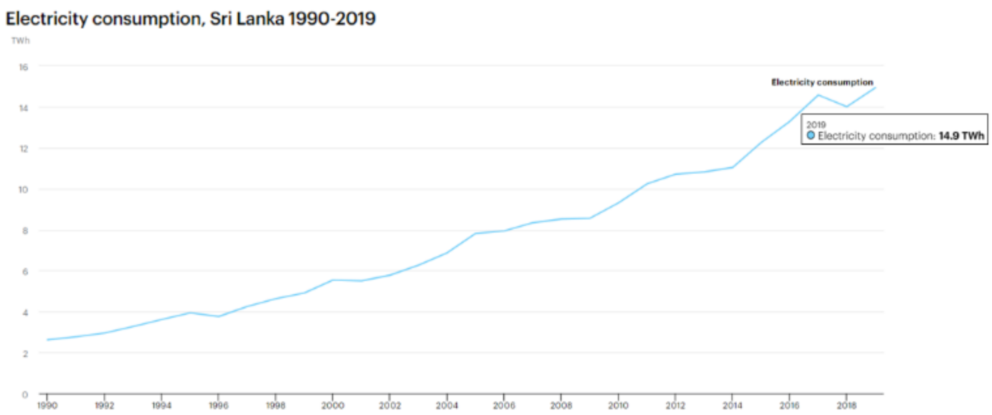

Figure 2. 3 Electricity consumption of Sri Lanka [19]

About 40% (2017) of the electricity produced in the country comes from the hydroelectric sector with an installed power of about 1.8 GW. The remainder comes from fossil sources, and the share of other renewables has a very small percentage, as is also shown in *Figure 2.4* [19].

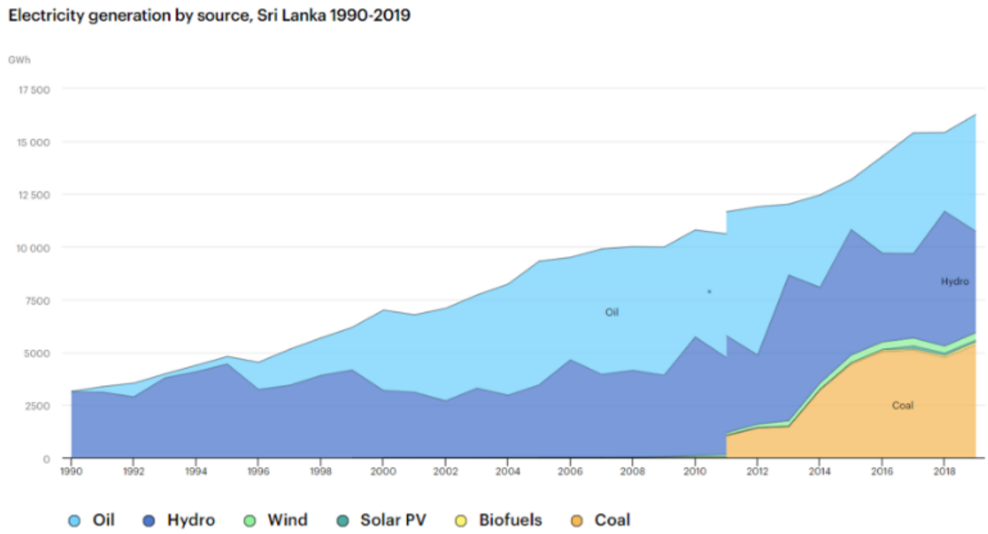

Figure 2. 4 Electricity generation by source - Sri Lanka [19]

From the IRENA (*International Renewable Energy Agency*) report on Sri Lanka published in 2021 [18], it is noted that in the years, from 2013 to 2018, energy imports from foreign countries both grew from 220040 TJ to 317060 TJ. The sectors with the highest energy consumption are the domestic (58%) and industry (39%). The report also indicates the growth of renewable energy in the year 2019-2020, which grew by 6.3%, largely thanks to the development of the wind (+124 MW) and solar (+15 MW) sectors. The country has set the goal of reaching 100% of energy production from renewable sources by 2050.

In [20] the problem of energy poverty in Sri Lanka was analysed. Most of the population has access to the electricity grid, according to data from CEB (Ceylon Electricity Board), the largest electricity company in Sri Lanka. However, many people do not use this energy to power appliances or for cooking, because the price of electricity is too high. Furthermore, in some rural areas, biomass is still used as the main source for cooking. This is the main cause of energy poverty for families in Sri Lanka, which is also often associated with income poverty. The study places a lot of responsibility on the energy policies to be undertaken in the coming years, not only as subsidies for the poorest families, but also as an information system. In fact, part of the population does not know the negative effects of the use of fossil fuels, or the use of biomass as a fuel, and therefore on the need to use renewable sources.

2.2 Selection of suitable sites for RES installation

The population of Sri Lanka is about 21 million inhabitants, with an annual growth of about 0.5% per year [21]. As can be seen from the *Figure 2.5* [22], the population is more concentrated on the south-eastern coast of the island. The northern area, on which there is not much information about, is the least densely populated area.

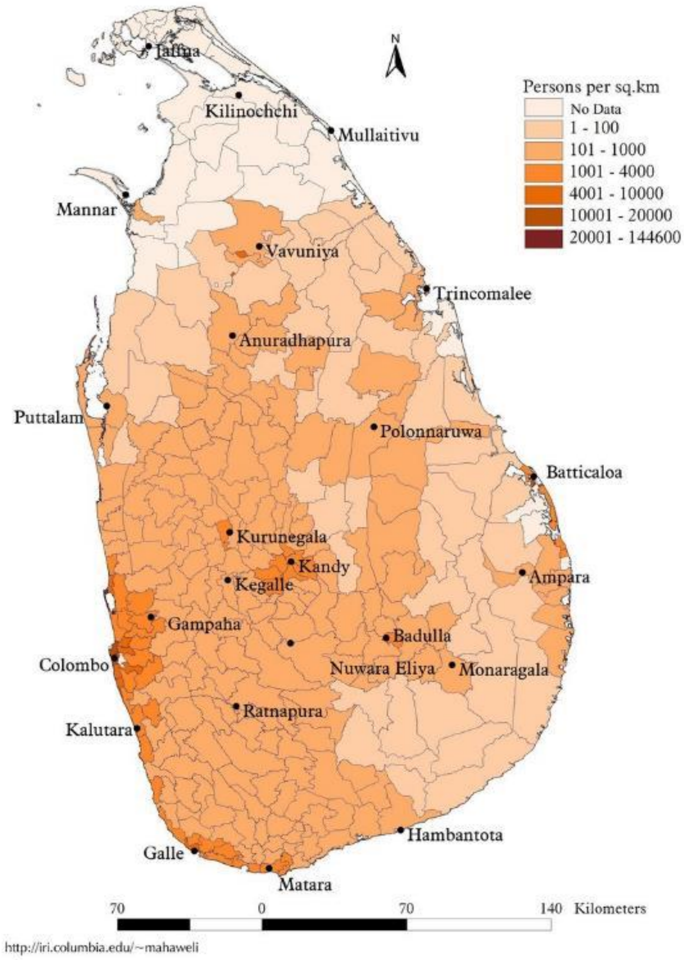

Figure 2. 5 Demographic distribution of Sri Lanka [22]

In this thesis work, the focus will be mainly on the installation of onshore wind generators and photovoltaic systems; without considering the potential of energy crops, the installation of offshore plants, and of new hydroelectric plants. The latter is already widely exploited in the territory.

2.2.1 Territorial Constraints

Many areas of Sri Lanka are subject to landscape constraints, in fact in the territory there are several natural parks, to preserve the flora and fauna of the territory. Coastal areas place a constraint on the development of photovoltaic systems. The *Figure 2.6* shows the presence of forest and wildlife area in the country [23].

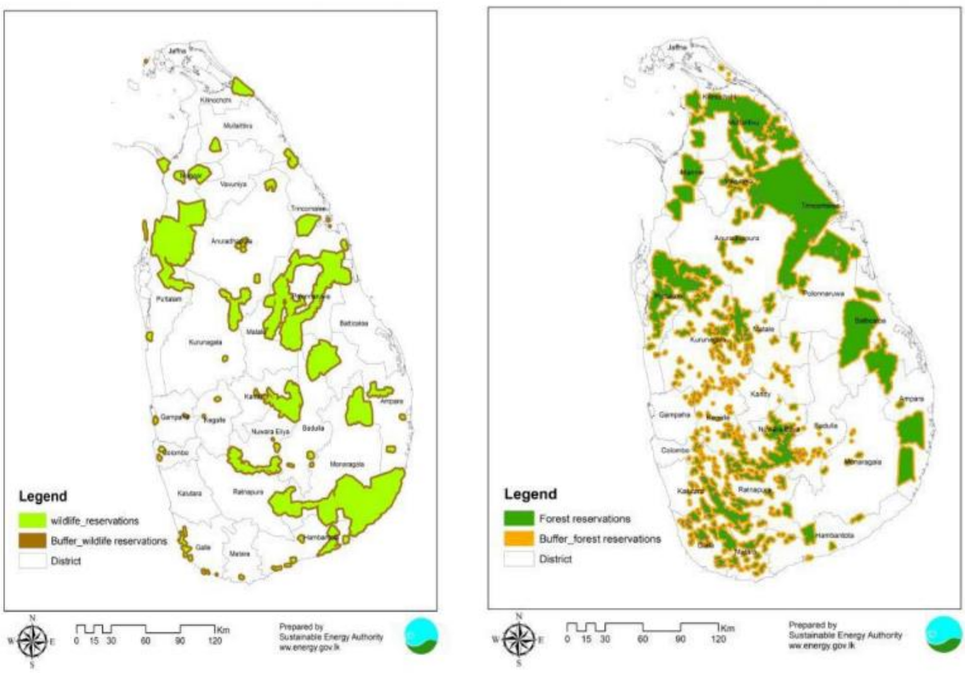

Figure 2. 6 Wildlife and forest reservation area [23]

According to international standards, wind generators must be installed at least 100 m from the road network. However, the choice of sites that are too distant from the road network (>2000 m) may not be convenient. It can create various difficulties in reaching the chosen site, both for the construction of the plant and for maintenance operations.

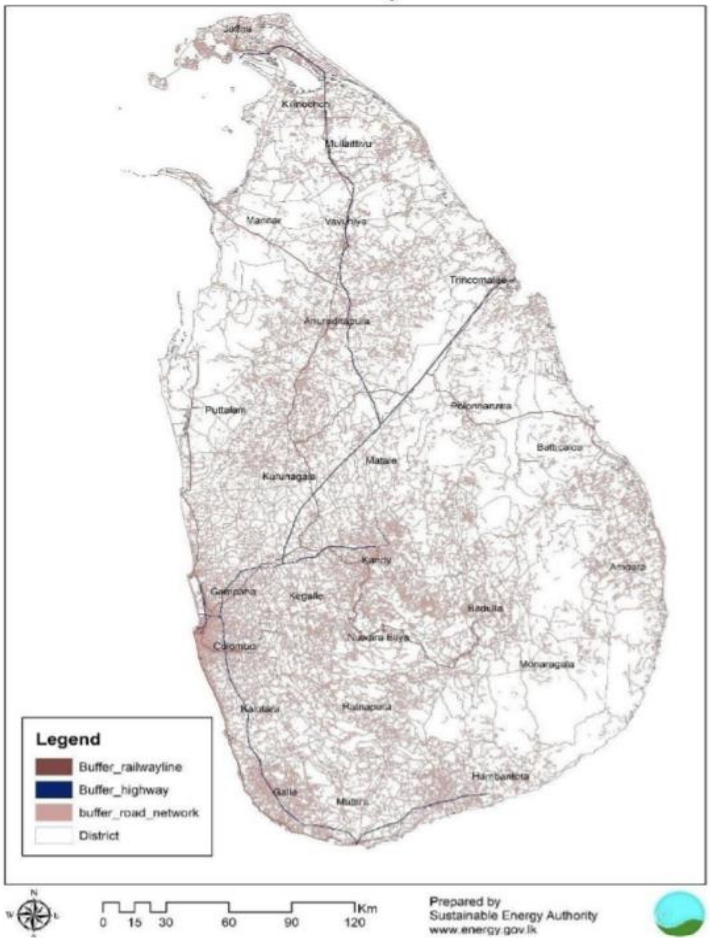

Figure 2. 7 Road network of Sri Lanka [23]

The proximity to urban centres is convenient, to reduce transmission losses in the grid, but it causes various problems for both photovoltaic and wind power plants. For photovoltaic systems the presence of many obstacles could increase the percentage of shading, with consequent loss of generated energy. For wind turbines, the proximity to urban centres could increase the degree of wind turbulence, causing loss of generation or safety problems. Furthermore, the presence of wind generators produces noise effects that could be annoying for citizens.

The map of urban centres is coherent with the population distribution map, shows in *Figure 2.5*.

Table 2.1, obtained from the information in article [23], shows the constraints imposed in the research for suitable sites for RES installation in the *Resource Development Plan 2021-2026.*

Criterion	***Buffer Area***	
	Wind	**Solar**
Forrest, Wildlife reservation	1.6 km	1.6 km
Archaeology sites	375 m	375 m
Coastal conservation areas	-	1 km
Road network	100 m	250 m
Railway	40 m	40 m
Urban centres	1 km	1 km
Water bodies	40 m	40 m
Airports		
International	15 km	2 km
Domestic	10 km	2 km

Table 2. 1 Territorial constraints for RES installation

2.2.2 Distance from the grid

A further constraint imposed is the proximity to the transmission grid. In [23] the plants are divided into two categories: 10-25 MW and higher than 25 MW. A coefficient was assigned to assess the feasibility of the plant. For example, for systems greater than 25 MW, a distance of less than 10 km from the grid is considered optimal for the installation of the system. Whereas greater than 50 km becomes prohibitive. Proximity to transmission grid is a very important issue to take into consideration. It is useful to install systems in areas where infrastructures are already present since the extension of the electrical grid is very expensive and could compromise the profitability of the project. Furthermore, the proximity of the new plants to the loads could reduce transmission losses.

The *Figure 2.8* shows the Sri Lanka transmission grid.

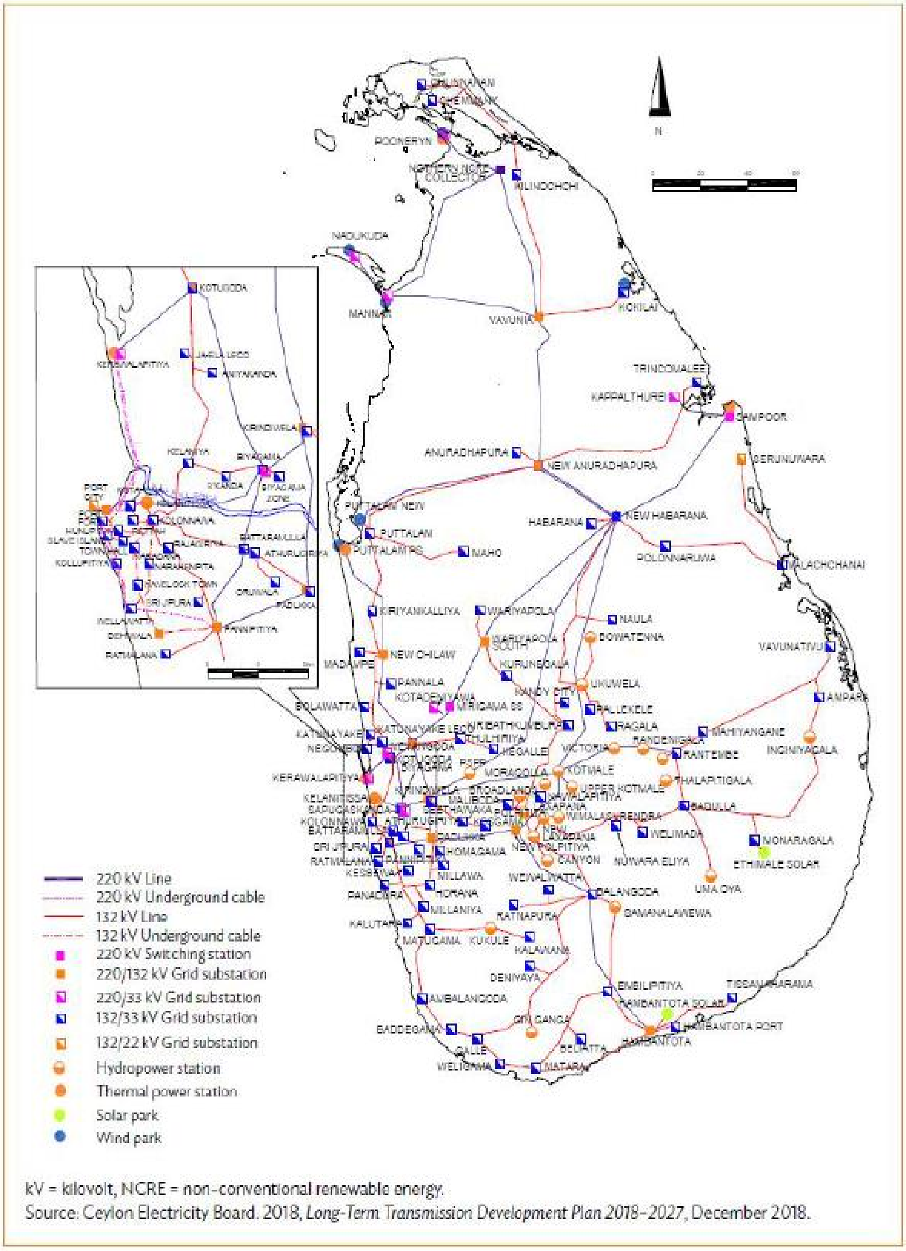

Figure 2. 8 Transmission grid of Sri Lanka [23]

It is possible to see in the *Figure 2.8* that there is a greater concentration of high voltage grid (220 kV) in the Central-Western area of the island, near the capital. In this area there are also several thermal and hydroelectric plants. The Southern part of the country is crossed by a 132 kV grid, while the Northern part is the least suitable for the installation of new plants.

2.2.3 Physical Constraints

Solar FV

Constraint:

- GHI (*Global Horizontal Irradiance*) higher than 1766 kWh/m^2 (*Figure 2.9*) [23].

The *Figure 2.9* shows how the areas with the highest irradiance are located on the entire coast of the island. However, in the coastal strip many constraints have been imposed on the installation of photovoltaic systems, as shown in *Table 2.1*. The Central-Southern areas, on the other hand, have a very low potential and the installation of PV generators in those areas is not convenient. This area is the most convenient for the proximity to the electrical infrastructure and urban centres: as it has been pointed out in the previous paragraph, there are several transmission lines and several cities with high electricity consumption.

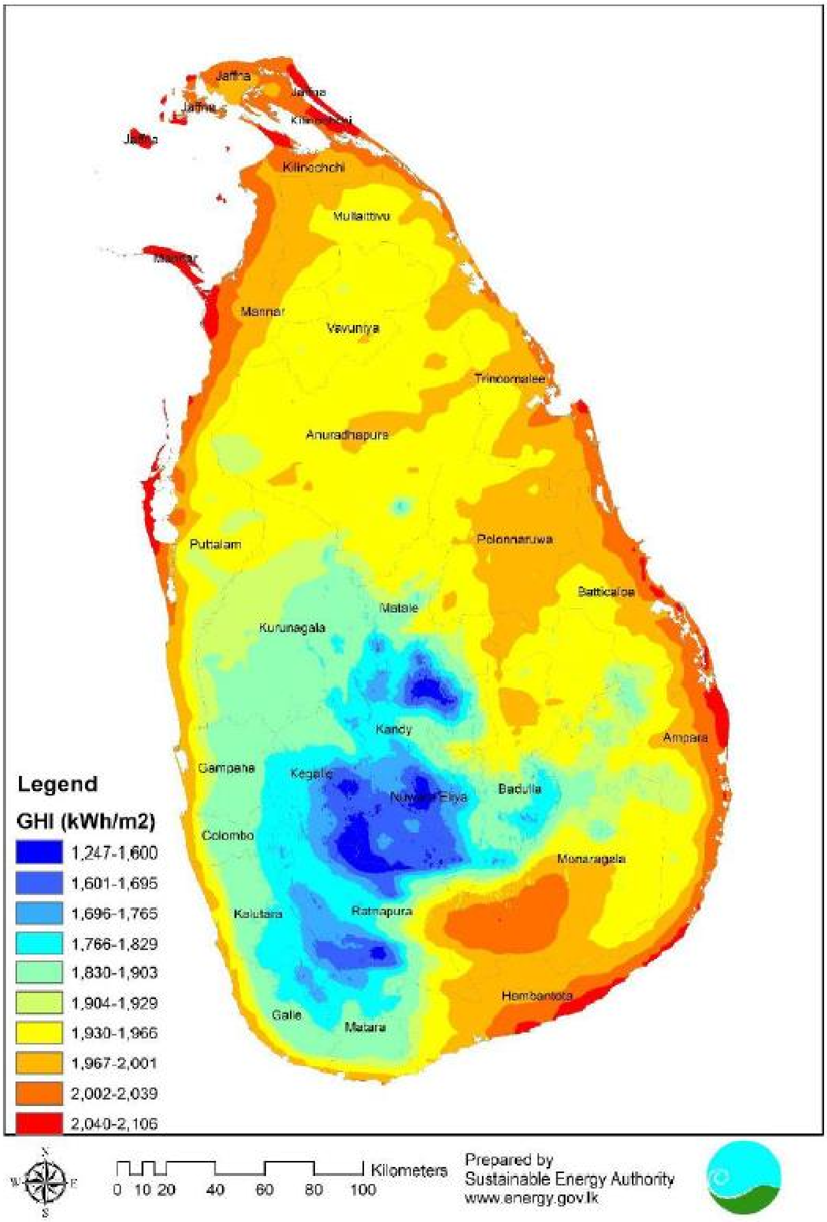

Figure 2. 9 Global Horizontal Irradiance [23]

Wind power

As expressed in the general part on wind power, wind speed is a fundamental parameter to be evaluated when analysing possible installation sites. In fact, the productivity varies with the cube of this value.

Constraints:

- Wind speed greater than 7 m/s at 100 m height (*Figure 2.10*) [23].

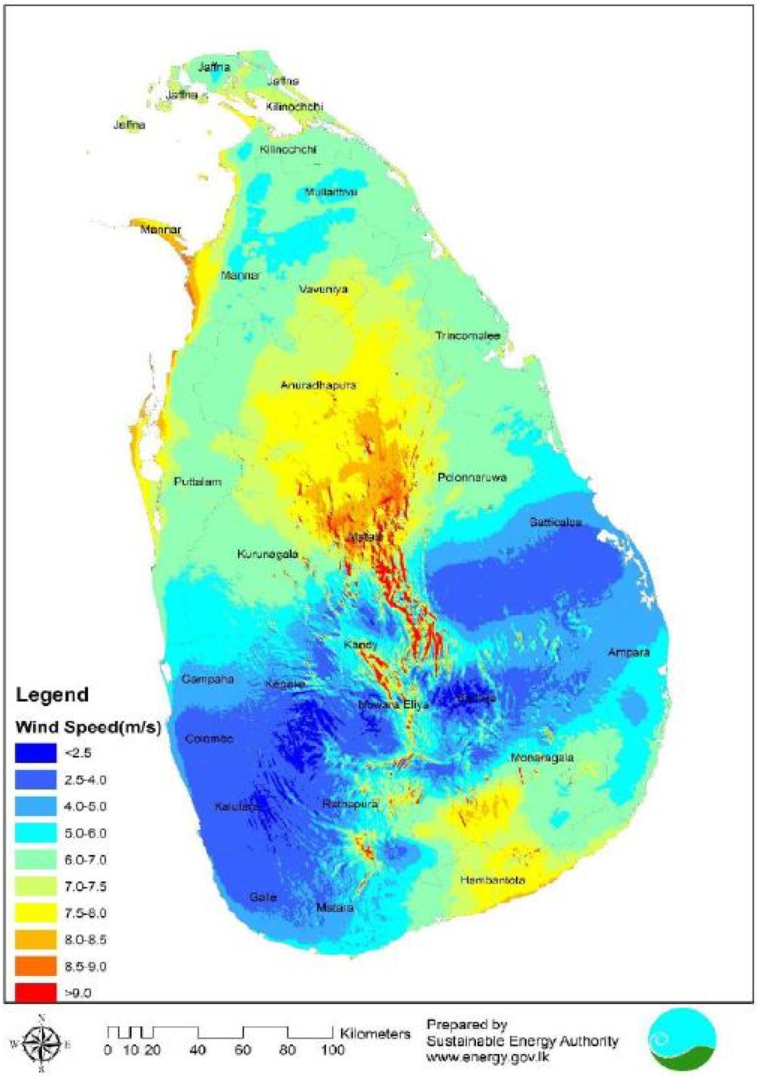

Figure 2. 10 Wind mean speed [23]

As in the case of solar radiation, the central southern part of the island is the least suitable for this type of installation. In the central area, on the other hand, there are very favourable areas, with an average annual wind speed of up to 9 m/s. Furthermore, the North-Western side of the island is also suitable for this type of analysis.

➢ The ground must have an inclination of less than 30% [23]

Too high ground inclinations are not optimal for the installation of wind generators since the speed and direction of the wind is altered.

➢ Roughness length

A roughness length that is too high slows down the speed and consequently the productivity of a wind generator. From the map in the *Figure 2.11* [24], the South-West area of the island is characterized by a higher roughness. The wind speed is the lowest in those areas, which therefore become prohibitive for the installation of wind generators. In the southern zone a high roughness length can be caused by the presence of some non-flat areas, as shown also in *Figure 2. 12*, or it could depend on the presence of different urban centres. In fact, *Figure 2.5* shows how most of the Sri Lankan population is concentrated in that area. In the northern part there is another area with a high roughness length. This area is flat and sparsely populated, so a high roughness could be due to the presence of forest areas. This hypothesis is consistent with the map in *Figure 2.6*, which shows several protected natural areas, including the Wilpattu National Park. However, the data for this specific area of Sri Lanka are insufficient to confirm this hypothesis with certainty.

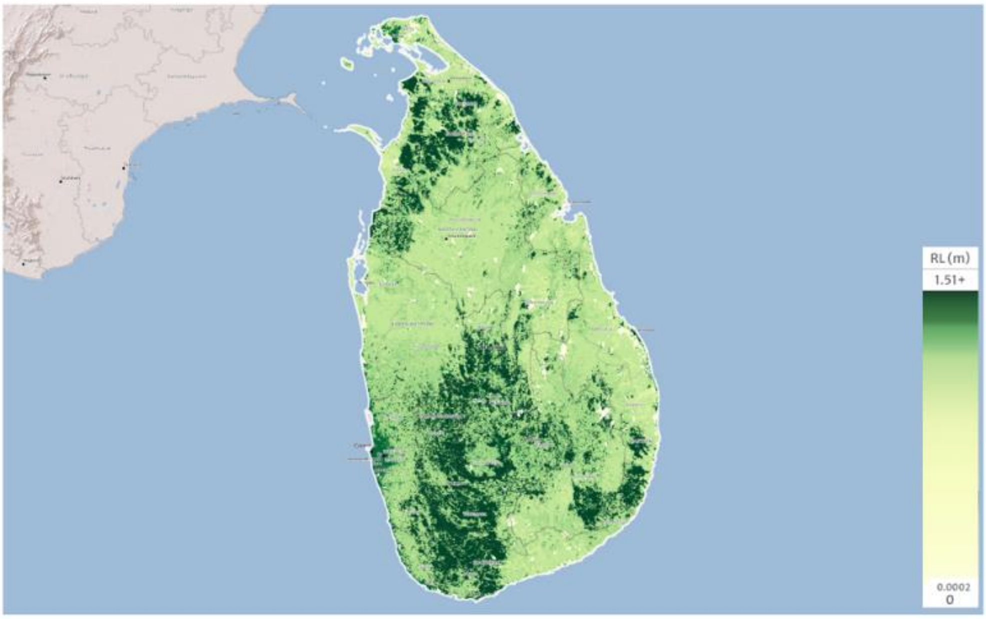

Figure 2. 11 Roughness length [24]

➢ Orography

From the *Figure 2.12* taken from the *Global Wind Atlas* website [24], it is possible to see how the country is mainly flat, except for the central area where the mountain range called "Central Highlands" is present. The orography has a great influence on wind generation, as the variation in the height of the ground changes the wind speed profile. In this area, therefore, the installation of new plants is prohibited not only for wind generation but also for the low solar radiation. Also, in this area there are several protected natural areas.

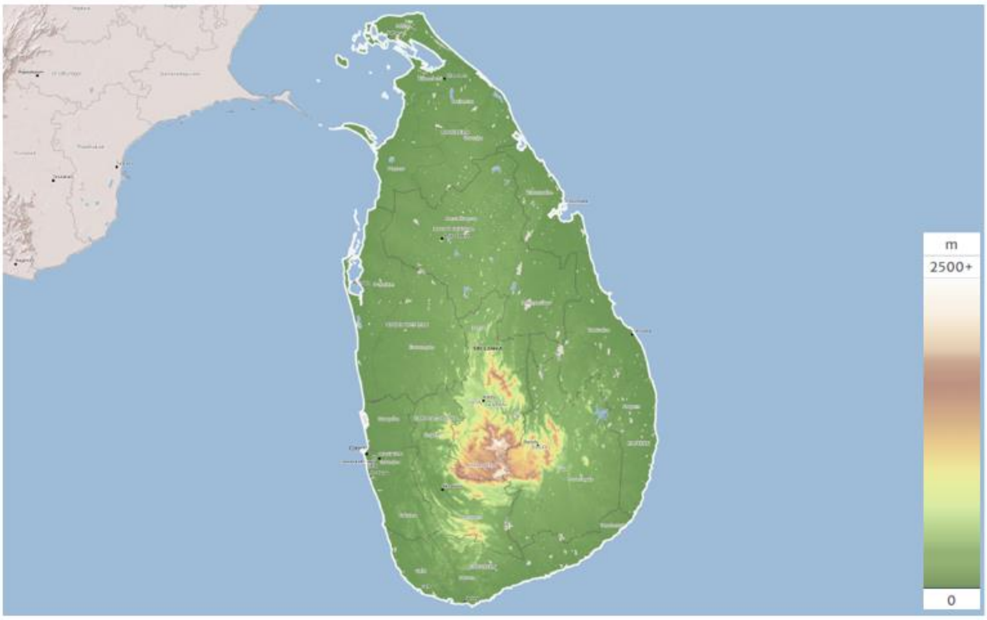

Figure 2. 12 Orography [24]

➢ The installation site must be located at a maximum of 270 m above sea level [23].

The installation of wind generators is a complicated and expensive process. For this reason, installation above 270 m could be prohibitive even if the availability of resources is high.

2.2.4 Results

To identify the possible installation sites of these plants, in [23] a weighted analysis of all the constraints was carried out. A coefficient was associated with each constraint, based on its convenience, and with different specific weight. For example, the distance from the transmission grid has a higher percentage than the territorial constraints.

The *Figures 2.13* and *2.14* show the main suitable areas to the installation of new renewable plants.

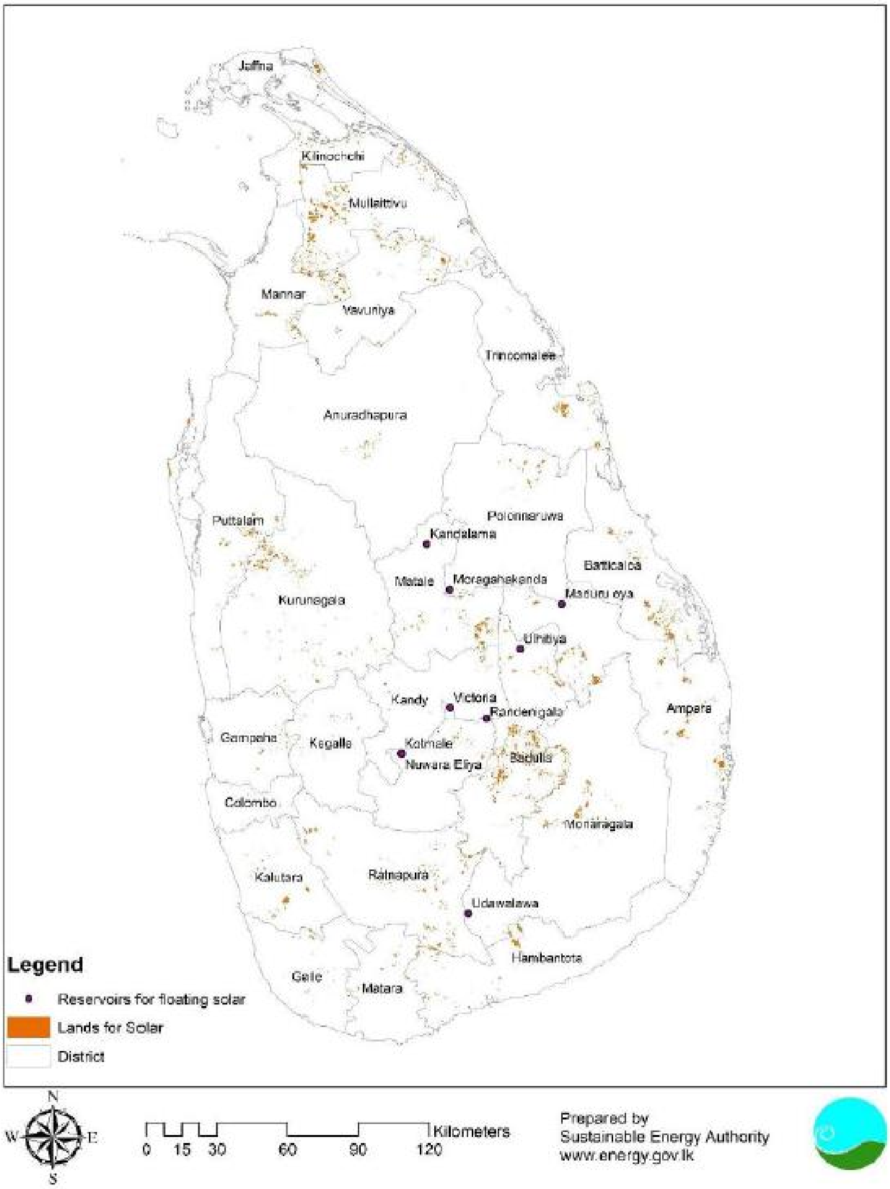

Figure 2. 13 Suitable areas for PV system [23]

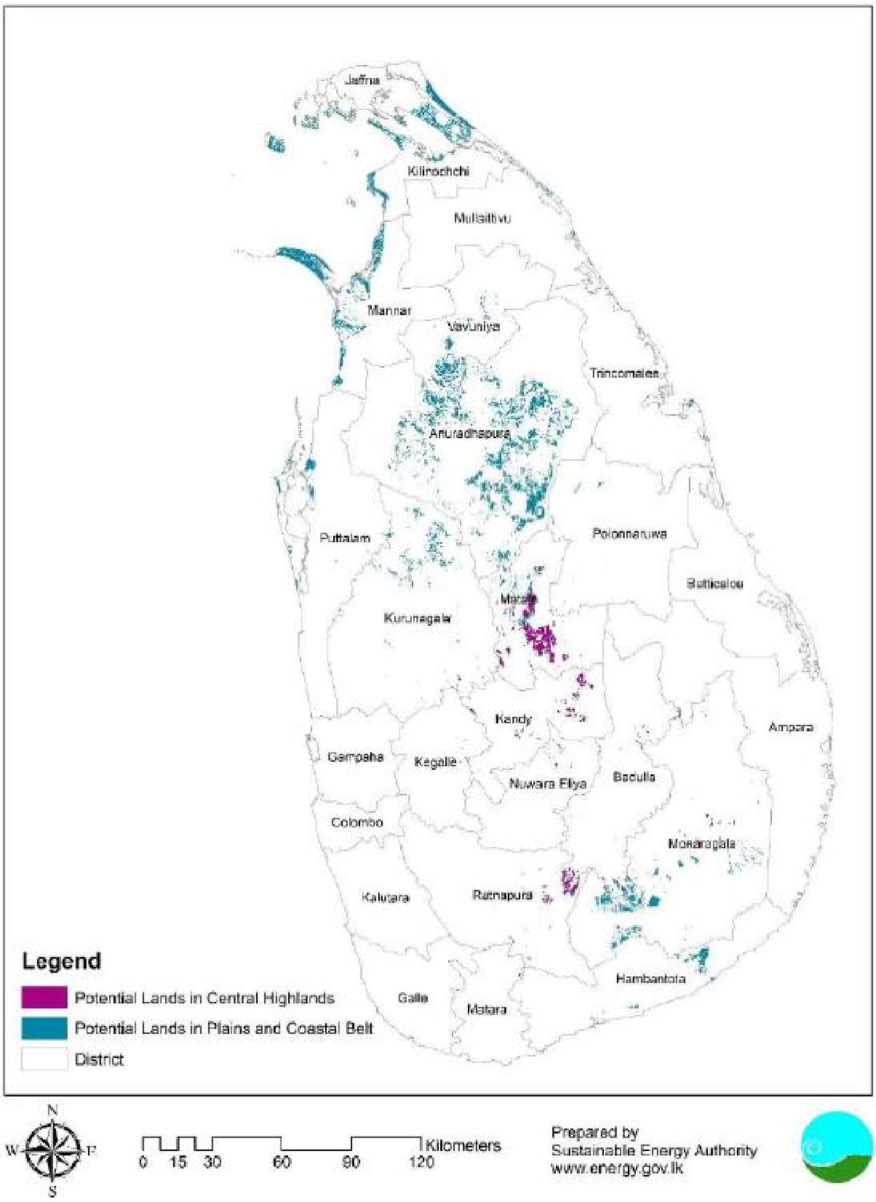

Figure 2. 14 Suitable areas for WT generators [23]

In [23] are presented some sites where the installation of new plants, both wind power and renewable, is in the planning phase. The analysis described above has already been performed for these sites. With the information present in the article, the map in the *Figure 2.17* was created, which shows the locations of these new projects. It can be seen that the installation of new wind farms is concentrated in the northern area and in particular on the western side of the island. This result is consistent with the map in the *Figure 2.14*, in which the most densely coloured area for the installation of these systems is concentrated in this area. In particular, in the proximity of the Pooneryn and Mannar areas, two projects of over 100 MW each are being developed. Even if these areas are the most suitable for the development of this technology, it is necessary to make a careful economic analysis to investigate the profitability of the plants, as in these areas the electricity infrastructures are weak.

By superimposing the figures of the suitable areas provided by the *Development Plan 2021-2026* [23] with the image of the transmission grid, it is possible to identify other useful sites for the installation of new systems.

These sites were selected based on proximity to the transmission grid and therefore in proximity to a 220 kV or 132 kV lines. From *Figure 2.15* for PV installations, the South-Western part was not considered, although being very well connected to the transmission grid and urban centres, due to the scarcity of resources in the area. The selected areas are located near the cities of Mallavi (North), Mutur (East), Nikaweratya (West) and Badulla (Centre). All the sites are located near the transmission grid, characterized by an excellent solar irradiance, and located in the areas suitable by the *Development Plan* (Areas in orange in *Figure 2.13*).

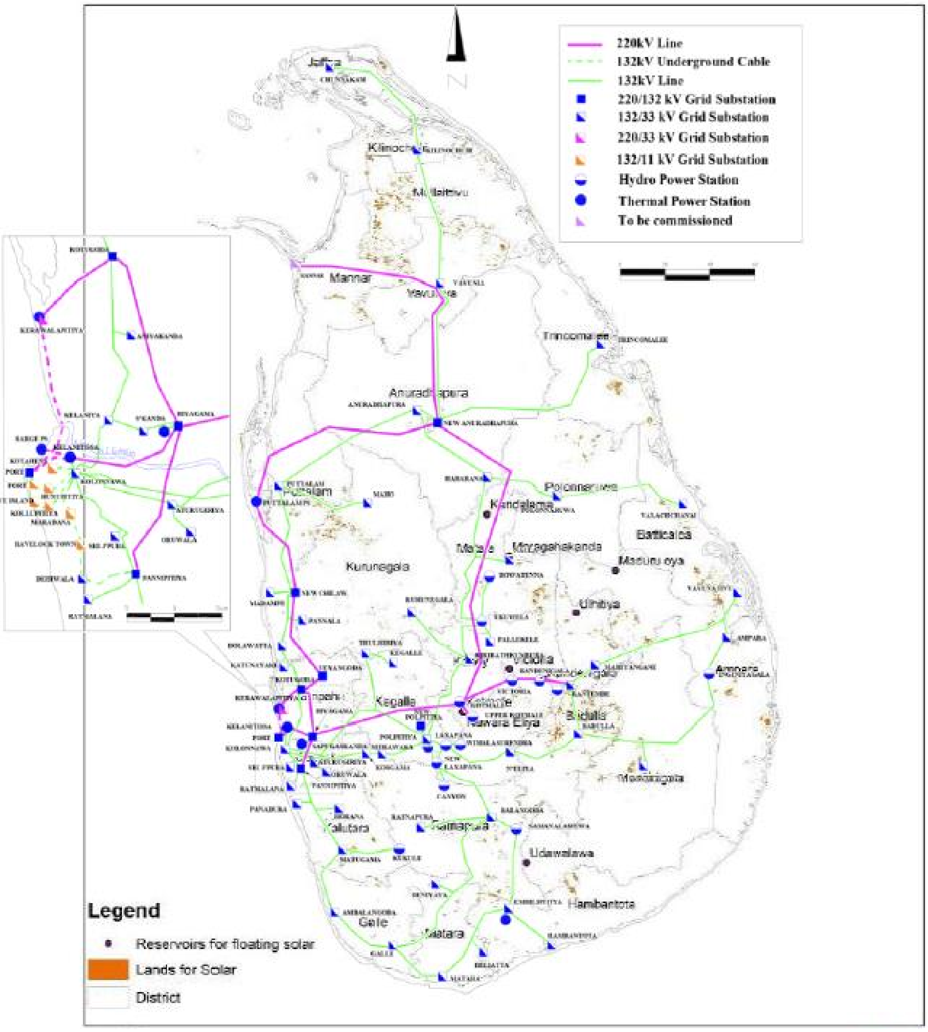

Figure 2. 15 Suitable sites for PV installations near to transmission grid

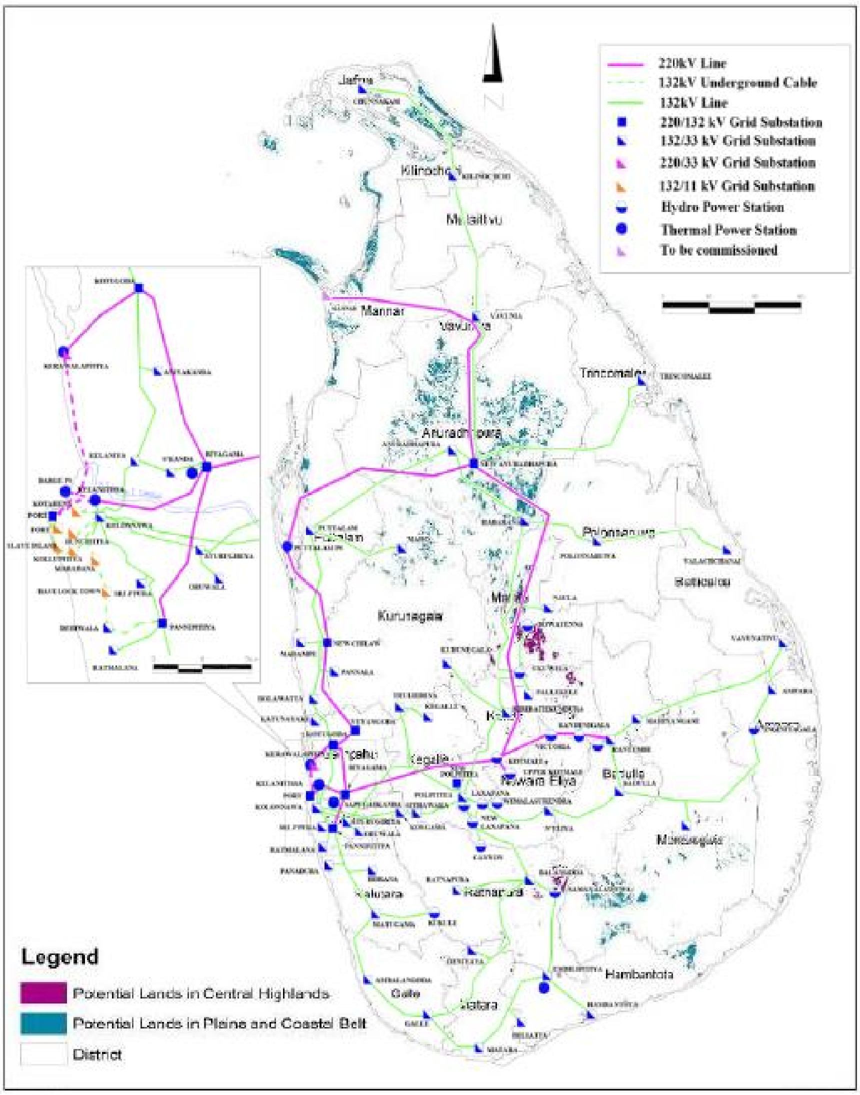

Figure 2. 16 Suitable sites for WT installations near to transmission grid

For the identification of new sites for the installation of WTs, the same analysis was performed. The sites in the northern part are the most suitable, in fact there are already projects for these places. On the eastern side of the island the mean wind speed is not sufficient. From *Figure 2.14* some suitable areas are in the central-northern part also characterized by the proximity to a 220 kV transmission grid. However, in this area there are several protected natural parks. The only site identified in this area is the one near Anuradhapura. Another site has been identified in the southern part of the island, Hambantota, where there is already a project for the construction of a PV system [23].

All selected sites are shown in *Figure 2.17*.

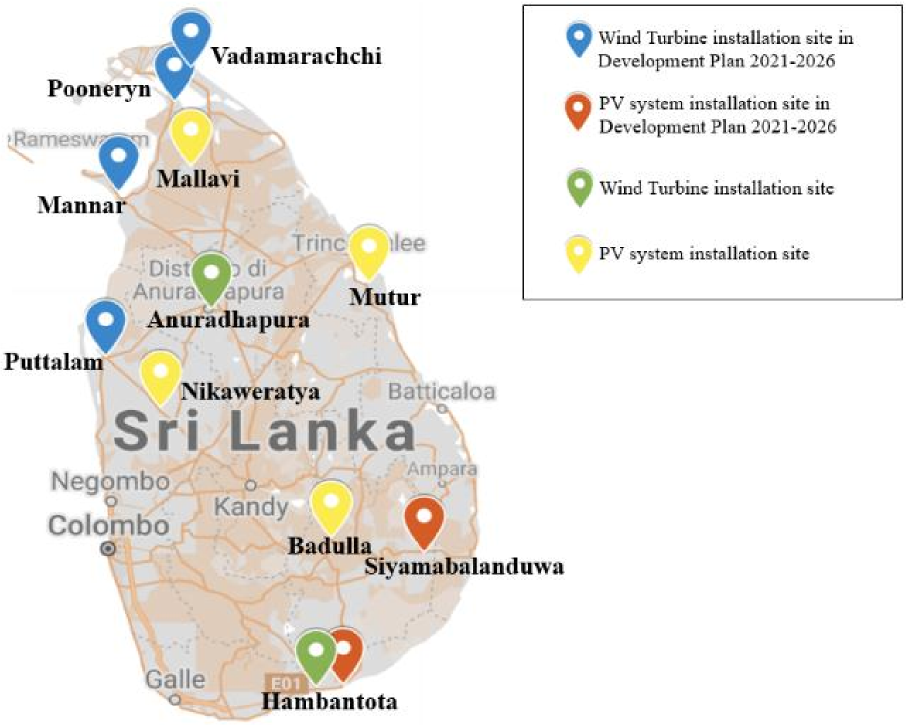

Figure 2. 17 Future development sites

Thanks to the use of the Google Maps software [17] and through its "Street view" function, it is possible to analyse the peripheral areas of the selected cities, in order to identify possible installation sites. Areas close to the road network, and in the absence of buildings, were analysed. *Figures 2.18* and *2.19* show two representative areas near the Mallavian and Anuradhapura cities.

Figure 2. 18 Representative area near the city of Mallavian [17]

Figure 2. 19 Representative area near the city of Anuradhapura [17]

	Type of installation	City	Coordinates
Site 1	PV	Siyamabalanduwa	6,902398, 81,559882
Site 2	PV + WT	Hambantota	6,175724, 81,127126
Site 3	PV	Badulla	6,975373, 81,043984
Site 4	PV	Nikaweratya	7,707983, 80,157418
Site 5	PV	Mutur	8,455347, 81,283298
Site 6	PV	Mallavi	9,143101, 80,302908
Site 7	WT	Puttalam	8,065025, 79,824678
Site 8	WT	Mannar	8,985175, 79,891962
Site 9	WT	Pooneryn	9,506586, 80,209742
Site 10	WT	Vadamarachchi	9,797507, 80,212122
Site 11	WT	Anuradhapura	8,297423, 80,392556

Table 2. 2 Possible sites for RES installations

Chapter 3

3 Energy policies and economic data for RES installation

In this chapter, various incentive schemes for the development of renewable sources have been analysed. In particular, the difference between the developing countries of South Asia and the developed countries of the European Union was highlighted. In particular, the Sri Lanka incentive system was discussed and compared with that of Italy, Germany and Spain. It has been noted that developed countries have had substantial growth in the installation of these systems in the first years of incentives and this has led to a change in the system itself, to control growth, through the introduction of the auction system. In Sri Lanka, on the other hand, the main energy policies focus on the spread of photovoltaics through contributions on the electricity fed into the grid.

Subsequently, the study focused on the analysis of some economic data useful for the design of these technologies. In particular, the installation costs of new plants were analysed, showing how the development of a market for these technologies leads to a reduction in general costs. The technologies analysed were those of photovoltaics, onshore wind and electrochemical batteries. In addition, the price of electricity was analysed, in particular the electricity selling price and the value of the electricity self-consumed.

Economic data found for Sri Lanka and other non-European countries refer to the country's local currency. For simplicity, all data are shown in [€], the conversion was done using the xe.com website [25].

3.1 Energy policies

Energy policies are a series of actions that a state takes to incentivize energy development. Among these actions are the incentives on the production of energy from renewable sources which will be explored in this paragraph, without considering the effects on the distribution and use of energy, which are also fundamental issues in a country's energy development system

3.1.1 Analysis of the energy policies in Sri Lanka

The continuing concerns about climate change push all the countries to take action to contrast this problem. Developing countries, such as Sri Lanka, face an ever-increasing energy demand. However, Sri Lanka has not the resources available to adequately support this growth. Sri Lanka must rely on fossil sources to cover its demand. The identification of energy policies is a key point for a sustainable development, relying on renewable sources, such as wind and solar, to cover the electricity load.

In [26] the concerns and actions taken by the state of Sri Lanka to combat climate change are presented. In 1992, the *National Environmental Action Plan* (NEAP) was drawn up, highlighting the problems on climate change and the possible disasters it would have brought in those years. In 1993 the Government of Sri Lanka also decides to join the *United Nations Framework Convention on Climate Change* (UNFCCC) [27]. The turning point for the State was the institution of the *Secretary for Climate Change* (CCS) in 2008; through this new institution, the *National on Climate Change Policies* (NCCP) were established. In 2016, Sri Lanka decides to sign the Paris Agreement outlined during COP-21 [28]. Subsequently the state establishes indicators and sets constraints (INDC) to be implemented by 2030.

The literature analyses different energy policies implemented in different countries. In Sri Lanka, a first approach to this type of incentive is already analysed in the early 1990s and is presented in [29]. The production of electricity from hydroelectric plants was encouraged through the Feed-in Tariff regime (FiT). With this scheme, the selling price of electricity from renewable sources is kept constant. During the first few years of use, the tariff was based on avoided costs, using the long-term generation planning model. This model was subsequently revised, leading to pricing at specific costs. With this scheme, the tariff is designed to cover the costs of the initial capital and those of operations and maintenance, established in the design phase.

The document in [30] describes the policies implemented in 2010 and then updated in 2016, within the "*Soorya Bala Sangramaya*" program to encourage the development of photovoltaic systems in the country. Between 2010 and 2016, the use of a *Net Metering* (NM) policy was used to increase the production from photovoltaic technology. A NM scheme works through the accounting of the net energy consumed by the customer, or rather from the metering of the energy withdrawn and fed into the grid. Through a bidirectional meter, the consumer is charged for the net energy consumption at the end of the billing period. The use of this incentive allows to use the distribution grid as a virtual storage system saving the installation costs of electrochemical batteries [31].

In [32] is presented the Tariff Structure of electricity price in Sri Lanka for encouraging the NM scheme. In this structure the price of electricity has been made proportional to electricity monthly consumption. In this way, by installing renewable systems with a bidirectional counter, less energy is purchased from the electricity grid and at a lower price than traditional consumption (*Table 3.1*).

Tariff Structure					
Tariff block [kWh] (Monthly consumption)	0-60	61-90	91-120	121-180	>180
Unit rate [c€/kWh]	3.4	4.4	12.2	14.0	19.7

Table 3. 1 Tariff structure of electricity consumption – Sri Lanka

With NM, if the consumer produces more energy than imports, it will only have to pay a minimal flat fee, and the net energy fed into the grid will be used as a credit for subsequent billing. If, on the other hand, the consumer imports more energy than the produced one plus any previous credits, it will have to pay a tax based on the net energy consumed in addition to the fixed tax. [33]

In 2016 to further increase solar generation, the Government of Sri Lanka implemented two other policies in addition to Net Metering: Net Accounting and Net Plus [32]. The **Net Accounting** scheme is very similar to the NM system but is applied only for photovoltaic systems. The net energy produced in excess is not converted into credits but is sold to the grid operator at 9.6 c€/kWh for first 7 years and 6.8 c€/kWh from the 8^{th} to 20^{th} years. If the imported energy is higher, the consumer will have to pay the net energy at the market price. With the **Net Plus** scheme, the consumer will be able to feed electricity into the grid which will be paid at the same rate as the Net Accounting. Its consumption will be quantified by another meter and the energy imported from the grid will be paid by the consumer to the market price [33]. *Table 3.2* summarizes the main information of the two incentive schemes.

	Net Accounting	Net Plus
Differences	The net energy is incentivized by the distribution grid (the net energy is difference between the energy produced by the plant and injected in the grid and the energy supplied by the distribution grid to the producer). If the energy withdrawn from the grid will exceed the energy fed in, the net energy will be paid by the consumer at the rate stipulated by the grid operator.	The consumer sells the electricity produced to the distribution grid. The imported electricity, will be measured by another meter and will be billed according to the current electricity tariff stipulated by the distributor operator.
Commonalities	- Billing period: 30 days - Duration of the incentive: 20 years - Incentive valid only for photovoltaic systems - Electricity incentive tariff: 9.6 c€/kWh for the first 7 years and 6.8 c€/kWh from the 8^{th} to the 20^{th} year	

Table 3. 2 Main information for Net Accounting and Net Plus scheme

In [34] a mathematical model and an implementation algorithm for Net Metering applied to a photovoltaic system is presented. In [35] a study was conducted on the various factors that influence people's attractiveness to use Net Metering, conducted for the State of Sri Lanka. It was analysed how this kind of incentive is technologically useful to satisfy an increasing of electricity demand by reducing the purchase costs from the grid. The study concludes that the slowed development of Net Metering does not concern technical reasons, but the concern is the Tariff Structure. In particular, the proportional scheme of the electricity tariff based on consumption prompted many large consumers to use the NM scheme. The electricity company that subsidizes this scheme could suffer serious financial losses. The operator is forced to raise the price of electricity with serious effects on small consumers. The NM scheme is very functional to encourage self-consumption, so when generation and load are in phase. In the case of Sri Lanka, the domestic demand is higher from 6 p.m. to 10 p.m., so, when there is no production by the photovoltaic system. For these reasons, the development of Net Metering in Sri Lanka did not have the desired results.

Regarding storage systems in Sri Lanka there are no direct incentives for the purchase of electrical storage systems, but the energy policies applied by the state could favour the spread of such systems, mainly integrated with solar PV systems.

3.1.2 Analysis of the energy policies in developing countries

In [36] an analysis was performed for some South Asian Countries such as Pakistan, India and Bangladesh, including Sri Lanka. These States represent Developing Countries with large resources of renewable and with energy problems. In this article the SWOT analysis was used to study renewable energy in these countries. SWOT analysis is used as a decision tool or to make strategic choices. It is divided into four parts (*Strengths, Weaknesses, Opportunities, and Threats*). In this article the *Strengths* are the potential of renewable resources in these countries. The *Weaknesses* are represented by the difficulty in procuring the technologies. The *Opportunities* are the energy policies used by the state and the *Threats* are represented by political instability, energy dependence on other countries and the presence of fossil sources in the territory. Among the countries analysed, India has the highest percentage of energy produced from renewable sources, about 9% (excluding hydroelectricity). India provides large subsidies on starting capital; however, it has the highest interest rates compared to other countries (12-15%). India also prefers to develop domestic manufacturing industries, thus setting an import tax. Pakistan prefers to develop new projects, often importing technologies from other countries. There are no general policies for subsidizing the development of renewable energy, and countries with similar resources use different incentive schemes, the main information are shown in *Table 3.3.*

In [37] the effect that the "Feed in Tariff" (FiT) energy policy has on the development of renewable sources in developing countries is shown, taking the situation in the Philippines as a case study. In particular, it was highlighted how this kind of policy is the most advantageous for encouraging small renewable plants such as photovoltaic and wind power plants. This incentive reduces the problem linked to the uncertainty of the source, making the investment safer. In Philippines the FiT is equal to 15.7 c€/kWh for photovoltaic systems and 13.3 c€/kWh for wind generators. It is also shown how large generation plants, both renewable, such as hydroelectric, and traditional, which cover a large part of the base load, are less attracted to this type of incentive. This occurs because these projects have long development and construction cycles, thus preferring *Project Finance* (PF) incentives. The PF are long-term investment that are collected by companies in the project phase, based on the future revenues that the plant will be able to guarantee.

Energy Policies	
Developing countries	
Pakistan	- Carbon credit - Net metering - Refinancing scheme: distributed generators can receive incentives with interest rates of 6% - Non-Income tax: No income tax for the sale of electricity from renewable sources [36]
India	- Competitive bidding - Subsidy: the government offers subsidies of up to 30% of the cost of initial capital for new renewable energy plants - Generated-based incentives: a subsidy of 0.6 c€/kWh produced is given, however this type of incentive is valid only for wind generators - Net Metering - Subsidy for photovoltaic rooftop: the Government offers subsidies from 30 to 70% of the cost of capital to install new photovoltaic systems on the roof, the subsidy varies according to the region of installation [36]
Sri Lanka	- Net Metering incentivized by the tariff structure - Net Accounting } 9.6 c€/kWh (first 7 years) - Net Plus } 6.8 c€/kWh (from 8th to 20th) [33] - Interest rate: the Government sets the interest rate for investments in photovoltaic systems on the roof and loans up to 1540 € at 6% [32] [36]
Bangladesh	- Feed in Tariff - Depreciation: 100% for photovoltaic (first year) e wind power (first 5 years) [36]
Philippines	- Feed in Tariff: for photovoltaic system equal to 15.7 c€/kWh, for wind generator 13.3 c€/kWh [37]

Table 3. 3 Energy Policies for developing countries

3.1.3 Analysis of the energy policies in developed countries

The European Union has shown a strong interest in energy policies in recent years. Among the main causes that have pushed important actions, there are the energy dependence of other states, the high and volatile prices of electricity, the increase in demand, the risks and security of supply and climate change. In particular, on this last issue, the European Union has undertaken very important actions and set ambitious objectives. In particular, with the introduction of the Green Deal, the European Union sets the goal of being carbon neutral by 2050 and reducing CO_2 emissions by 55% by 2030 compared to the values recorded in 1990. To achieve these objectives, the first the step to be taken is the decarbonisation of the energy sector, which can take place by encouraging the production of electricity from renewable sources. In this scheme each member state must undertake long-term national political actions with the global goal stipulated during the Paris Agreement to keep the global temperature increase below 2 °C compared to 1990. As for renewable sources the EU, in 2018 with *Directive (EU) 2018/2001* [38] set the goal of reaching 32% of energy consumption produced from renewable sources. Also, in 2021 it was proposed to increase the percentage to 40% through 2030. Each Country sets its own goals and individual actions to achieve them ten-year development plans, showing progress through every two years. The Horizon 2020 programs and the subsequent Horizon Europe were the main projects with which the EU finances and supports the development of new projects in the energy sector. [39] [40]

The following paragraph shows some specific actions implemented by some EU countries regarding the diffusion of renewable sources in the country. The countries analysed in this study are Italy, Germany, and Spain.

Italy

In Italy the feed-in tariff was supported by the "*Conto Energia*" (CE) program, but it has been abolished starting from 5 August 2013 for new photovoltaic systems.

In [41] the development of feed-in tariffs (FiT) in Italy was analysed. From 2003 to 2012, the scheme for PV systems was changed five times. In its latest version, which came into force in 2012, the PV plants were divided into three categories: I the traditional ones (TPV), II those integrated with buildings (BIPV) and III concentrator photovoltaic systems (CPV). The article in [42] highlighted the

FiT incentive system in Italy, and its evolution over time. Each version of the CE has set objectives for the installation of new plants; when certain objectives were achieved, the incentive scheme was modified. Up to the fourth version of the "Conto Energia" a premium rate was paid for each kWh of electricity fed into the grid. Between the first and fourth version, it can be noticed a reduction in the tariff. In the fifth version, an all-inclusive tariff was introduced for the share of electricity fed into the grid. The premium tariff is only applied to self-consumed energy. In this way, the on-site consumption of electricity by the producer is promoted, limiting the sale of energy. In the previous versions of the CE, all the kWh produced by PV plants received incentives.

More information on the FiT is shown in the *Table 3.4*, in which the values relating to the fourth (2012) and fifth (2013) version of the "*Conto Energia"* are reported:

FiT	**TPV [c€/kWh]**		**BIPV [c€/kWh]**		**CPV [c€/kWh]**	
	4th CE	5th CE	4th CE	5th CE	4th CE	5th CE
1 kW < P < 3 kW	22.1	9.4	41.0	16.0	35.2	13.3
3 kW < P < 20 kW	20.2	8.3	41.0	16.0	35.2	13.3
20 kW < P < 50 kW	18.9	6.9	37.3	14.9	35.2	13.3
50 kW < P < 200 kW	18.9	6.9	37.3	14.9	35.2	13.3
200 kW < P < 1 MW	15.5	4.2	34.5	13.5	30.4	11.9
1 MW < P < 5 MW	14.0	3.1	34.5	13.5	26.6	9.2
P > 5 MW	13.3	2.4	34.5	13.5	26.6	9.2

Table 3. 4 Feed in Tariff incentives in 4th and 5th version of Conto Energia - Italy

In [43] it is indicated that in the latest version of the CE the incentive rate is on average equal to 0.11 €/kWh and is limited to self-consumption for photovoltaic systems. In [44] there is a study carried out to describe the results of energy policies of a developed Country, such as Italy. Through the implementation of the CE program, Italy has increased the installed power of photovoltaic systems by 120% per year, installing 17.6 GW by 2018. One of the primary benefits of this scheme was the reduction in the cost of installing new photovoltaic systems, from 7.2 €/W to 1.3 €/W. In accordance with this reduction also the capital-grant equivalent of FiT has undergone a decrease over the years, from 7.5 €/W in 2006 to 3.6 €/W in 2018. As regards incentives through the FiT, the study noted how the system could be more efficient. In Italy there was an over-dimensioning problem of the tariff and some political choices have negatively influenced the use of these incentives. In Italy and in Germany, many national companies were not yet able to compete with the installation costs offered by competitors from other Countries.

Another incentive scheme widely used in Italy is the "*Scambio sul Posto*" (SSP). One of the main advantages of renewable systems, such as photovoltaic and wind power, is the possibility of combining these systems directly with a load, in this way the consumer is able not only to consume energy but also to produce it. The main advantage is the saving of energy which is not purchased by the grid. Within this context, the SSP incentive system is used to provide the consumer with an economic incentive. Through this system, the distribution grid is used as a virtual storage system for electrical energy. When there is an excess of energy, it is fed into the grid, while when there is a deficit, it is taken from the grid. The energy withdrawn from the grid is generally paid at the market price; thanks to the "*Scambio sul Posto*" system, it is partially reimbursed by the electricity grid operator. The calculation of this reimbursement is carried out by accounting for the energy fed into the grid and the energy withdrawn from the grid. This calculation also takes into account the difference in the price of electricity in the market, based on the day and year. [43] shows the calculation of the "*Scambio sul Posto*" rate, it takes into account various parameters, such as the economic value of the energy withdrawal, calculated on the basis of the national price of electricity; the economic value of the input, which depends on the zonal price of electricity; and some bonuses are also considered, such as tax refunds. As a reference example in [45] is shown the calculation of the "*Scambio sul Posto*" for a photovoltaic system of 150 kW for 2012. Assuming some hypotheses, the energy fed into the grid is valued at 10 c€/kWh and that withdrawn at around 8 c€/kWh. Through these values and with the measurement of energy, it is possible to calculate the value of the economic contribution that the GSE (*Energy Services Manager*) recognizes to the customer on an annual basis.

The economic contribution paid by GSE is calculated with the following formula:

$$C_s = min[O_e, C_{ei}] + CU_{sf} * E_s$$

(3. 1)

where O_e [€] represents the price of electricity taken from the grid and paid by the user and calculated on the basis of the "*Prezzo Unico Nazionale*". C_{ei} [€] equivalent of the energy injected, represents the economic value of the energy injected into the grid based on the zonal price of the electricity supply. CU_{sf} [€/kWh] is the annual flat rate unit exchange fee. The latter coefficient varies according to the power of the system, in particular if it is higher or lower than 20 kW. It depends on the annual flat-rate exchange relating to grid (CU_{Sf}^{reti}) and the annual flat-rate exchange relating to general system charges (CU_{Sf}^{ogs}). Finally, E_s is the net energy exchanged that is equal to the minimum between the energy injected and the energy withdrawn in an entire year.

The value of Cs depends on two terms, as shown in the equation; the first represents an energy share and the second a services share. The latter allows the costs incurred for the use of the grid to be returned to users.

Case study of "Scambio sul Posto": Adrano (CT)

All the data and formulations for this case study are present in the work of the article [46]. This study shows the application of the calculation of the "Scambio sul Posto" scheme to a case study in the municipality of Adrano (CT) in Italy.

The analysis was carried out for a photovoltaic system installed in a school. It should be noted that in this type of installation the load and generation are almost in phase. The peak demand for electricity coincides with the maximum production of the photovoltaic system, i.e., in the time slot called F1. However, in the summer months (July and August), when the PV plant has a high productivity, the load is minimal. The optimization analysis carried out with the aim of maximizing self-sufficiency calculated 90.8 kW for the PV and 144.7 kWh for the storage battery as the optimal size of the system. In this case the self-sufficiency is equal to 91.5%.

Each supplier will have to pay for the absorption of the electricity grid; if the user participates in the SSP incentive system, then the GSE will have to pay a contribution (Cs) based on the balance of power injected and withdrawn as described in the previous paragraph.

The following *Table 3.5* presents the calculations to be carried out for the evaluation of the C_S contribution:

$$C_s = min[O_e, C_{ei}] + CU_{sf} * E_s$$

C_{ei}	$$\sum_{h=1}^{n° ore anno} [E_{I,h} \cdot P_{Z_{MGP},h}]$$ (3. 2)	$E_{I.h}$ electricity fed in the grid $P_{Z_{MGP}.h}$ hourly zonal price	$P_{Z_{MGP}}$ [€/MWh] Nord 51.3 Sud 50.9 **Sicily 62.8**
O_e	$E_P * PUN$ (3. 3)	E_p electricity withdraw in the grid PUN average monthly prices	PUN 52.3 [€/MWh] (annual average)
CU_{sf}	$CUsf^{reti}$ + min $(CUsf^{ogs}; annual\ limit)$ (3. 4)	$CUsf^{reti}$ Unit exchange fee relating to the grid $CUsf^{ogs}$ Unit exchange fee relating to general system charges.	[c€/kWh] CU_{Sf} 7.5 CU_{Sf}^{reti} 2.1 CU_{Sf}^{ogs} 5.4
E_s	$E_S = \min[E_i; E_p]$ (3. 5)	Net energy exchanged	

Table 3. 5 Calculation of Cs contribution

The calculation of the annual fee is the most complicated parameter to obtain. For plants over 20 kW that do not receive any incentives, connected to non-domestic LV (Low Voltage) users, the calculation of the annual limit takes into account the unitary fees for the flat-rate exchange with the grid and the reference value calculated as the difference between the annual limit and the average market price of the hours between 8:00 and 20:00 recorded in the previous calendar year.

The excess energy fed into the grid can be sell by the operator, but the customer has to pay the VAT (*Value-Added Tax*) (22%), or it can be converted in credit that can be used for the following year (no additional taxes is imposed).

The *Table 3.6* shows the results of the calculation of the tariff. The two cases shown in the *Table 3.6* refer to maximizing self-sufficiency and NPV (*Net Present Value*) after 25 years. In the second case, the installed power is 56.3 kW and no storage battery has been installed. In both cases, the annual remuneration by the GSE, or the *Scambio sul Posto* contribution, has a significant weight. This contribution must be subtracted the contribution to be paid to the GSE, i.e., a taxation consisting of a fixed and a variable part for the management, verification, and control costs.

As described above, the surpluses can be used as credit for future accounting or collected in monetary form. In this case, state taxes will then be applied to the amount.

	Max. Self-Consumption	Max. NPV
PV power installed [kW]	90.8	56.3
Battery storage capacity [kWh]	144.7	-
NPV after 25 years [€]	54813	141073
Self-Consumption	91.5%	52.3 %
Annual Production by FV system [MWh/anno]	125.6	87.4
Total load [MWh/anno]	59.5	59.5
Annual injection in the grid [MWh/anno]	68.9	56.3
Annual absorption by the grid [MWh/anno]	5.1	28.4
Annual exchange with the grid [MWh/anno]	73.9	84.7
Annual Self-Sufficiency [MWh/anno]	54.4	31.1
$C_{ei} = E_I * P_{Z_{MGP}}$ [€]	4323	3534
$O_e = E_{PR} * PUN$ [€]	266	1 486
$CU_{sf} \cdot E_s$ [€]	384	2144
$C_s = \min(O_e, C_{ei}) + CU_{sf} \cdot E_s$ [€]	650	3631
$C_s / \min(absorption, injection)$ [c€/kW]	12.8	12.8

Table 3. 6 Main results for case study of Adrano [46]

The main advantage of using this incentive scheme is self-consumption. The average price of electricity in Italy is around 25 c€/kWh. The exchange with the grid is instead valued by the operator at around 10 c€/kWh. In the case study is equal to 12.2 (25-12.8) c€/kWh and this value depends on different parameters, as described above. In this case, even adding the installation costs of the PV system, the total price for each kWh produced is lower than the 25 c€/kWh paid on the electricity bill without this incentive scheme. However, care must be taken if a storage battery is also installed. Another simulation presented also in [46] is performed with the same parameters of the simulation in which self-sufficiency is maximized, but without installing the storage battery. It can be seen how a doubled NPV is obtained compared to the previous case.

It can be assumed in principle that the highest economic convenience occurs in the case in which the energy produced on site is exploited to the maximum, subsequently there is an exchange with the grid, to be used as a virtual storage system. Finally, the installation of the storage systems is evaluated.

From the information of the "*Decreto Legislativo n.199*" of 8 November 2021 [47] and entered into force on 15 December 2021, the "*Scambio sul Posto*" system has been abolished. Furthermore, for plants operating with this system there will be a gradual conversion to other mechanisms by 31 December 2024.

The other mechanisms that the plants can access are the "*Ritiro Dedicato*" and the "*Registri ed Aste*" system.

With the "*Ritiro Dedicato"* [48], the electricity not consumed is fed into the grid and will be purchased by the GSE. In this case, unlike "*Scambio sul Posto*", the grid is not used as a virtual storage system, but each net kWh injected will be paid to the GSE. Determining the average monthly price depends on several parameters, including:

- Time slot (F1, F2 and F3);
- Market area, identified by different geographical areas.

As an example, the values for the F1 time slot in Sicily in 2021 are shown. In January the value is 63.8 [€/MWh] and reaches 198.4 [€/MWh] in October [49].

With the system of "*Registri ed Aste*", the incentive is recognized for net energy. This parameter represents the minimum between net production and the energy actually injected into the grid. To access this type of incentive, the plants are divided into four categories and based on the installed power they must be registered in a register (plants less than 1 MW) or participate at auction (higher than 1 MW) [50]. The incentive can be provided as a "*Tariffa Omnicomprensiva*" (all-inclusive tariff) or "*Incentivo*" (incentive). The tariff calculation is performed starting from the reference tariff for each type of system, from which a percentage determined in the auction and register phase by the manufacturer will be subtracted. This rate may suffer a further reduction if certain constraints and timelines are not respected. In the case of incentives with "*Tariffa Omnicomprensiva*", the energy fed into the grid is remunerated as described above. In the case of an "*Incentivo*", the hourly zonal price of electricity will also be subtracted to the tariff. However, in this case the energy produced remains available to the producer.

Germany

Germany was one of the first nations in the world to take political action to subsidize the deployment of renewable energy. Through the EEG system (*Erneuerbare Energien Gesetz*), a tax is introduced which is paid by final consumers to incentivize the development of these sources. Thanks to this fund, producers receive a tariff for each kWh fed into the grid. In [51] the calculation of this tax is analysed; it results in the difference between the price guaranteed to suppliers for the energy injected and the actual market price. According to this study, the tax has increased in recent years reaching 6.9 c€/kWh in 2017, compared to 2.1 c€/kWh in 2010. This is due to the reduction in the market price over time. In this study, however, it is possible to note how the incentive rate has decreased over the years. For solar PV it equals 12.2 c€/kWh in 2017, if the installed power is less than 10 kW, but in 2006 the tariff was equal to 51.8 c€/kWh. The use of this scheme has brought the installed power of photovoltaic systems from 2.9 GW (2006) to 42.3 GW (2017). As regards the wind sector, the incentive system in Germany for this source was analysed in [52] until 2014. From 1991 until 1999, thanks to the StrEG system (*Stromeinspeisungsgesetz*), the tariff was paid by the distributor to the producer, according to the market analysis of the previous two years. With the introduction of the EEG system, the tariff changed over time. In the first 5 years it was higher, but the period could be extended based on the calculation of the turbine's productivity and therefore it depends on the place of installation. In the second period, the tariff was fixed at a lower price. In 2010, the initial incentive was equal to 9.1 c€/kWh and the base incentive equal to 5.0 c€/kWh. The total installed capacity increased to 26.8 GW compared to 55 MW in 1990. In 2017 the system was transformed into auctions and prizes, abandoning the FiT incentive.

In [53] it was analysed how the feed in tariff system has had little success in recent years. This is due to the increase in the tax that each taxpayer must pay to subsidize the plants and strong popular criticism has shown that in reality large consumers, such as very energy-intensive companies, are actually exempt from paying this tax. The strong growth in the installation of PV systems found the German government unprepared, in fact many PV plant manufacturers were unable to compete on the market with respect to technologies from China. For this reason, the government was forced to introduce an import tax for modules from China. Furthermore, the study aims to highlight how the development of PV systems incentivized by feed in tariff has almost reached saturation. The study proposes the development of an energy mix with other renewable sources to meet the national sustainable development goals.

Germany was one of the first countries in the world to use the auction system as an incentive scheme. In [54] it is shown how the German EEG has been changed from 2017 onwards. The system of incentive tariffs has been abandoned and a new system has been introduced, in which the incentive is paid thanks to the competitive systems of auctions. During the auction phases, the power account is assigned, while the incentive is paid for each kWh produced. As with the FiT system described above, also in this case it is the consumer who subsidizes this mechanism with a tax on the electricity bill.

The auctions are divided according to the technology and the size of the plants. Participants specify the prize they would like to receive for each kWh produced. The plants that have won the auction, sell the energy produced on the market at market prices, and subsequently receive the incentive as the difference between the price determined on the basis of the auction and the market price.

In [54] the results of some auctions held in Germany for photovoltaic and wind systems are shown. For photovoltaics, the price of the offers was 9.2 c€/kWh in 2015 and 4.9 c €/kWh in 2019, showing a constant decline until 2018 and a slight increase in 2019. For wind power, there was a rapid decline in prices in its first year (2017), going from 5.7 c€/kWh in the first months of the year to 3.8 c€/kWh in November. In the following years, a growth followed by a period of stability mainly due to the reduction in offers.

In Germany, there are not direct subsidies for the increase of storage systems. However, several strategies have been put in place to increase the installation of these systems. For example, for small-sized PV plants (less than 30 kW) combined with a storage system, funds that allow loans with subsidized rates and subsidies are available. With the "Battery 2020" program, grants of up to 50% of the capital are foreseen for the design of new lithium-ion systems [55]. In [56] it is shown how another important element for the diffusion of storage systems was the increase in the price of electricity and the reduction of FiT. The plants can feed into the grid at an incentive price only 60% of their production. With the government's willingness to shut down several nuclear power plants, the price of electricity has risen. This difference between the price of the energy injected and withdrawn pushed many users to invest in storage systems.

Spain

In Spain, through the "*Real Decreto 661/2007"* [57], the production of energy from renewable sources and cogeneration technology is encouraged. The incentive system is based on two schemes. The first provides for the payment of a regulated tariff to plants that decide to inject electricity into the distribution or transmission grid. The second instead provides that the producer receives a tariff calculated according to the electricity market prices plus a possible production premium. The wind and solar PV plants, the incentive system takes place through the regulated tariff. Therefore, the sale price is kept constant for each kWh fed into the grid. For wind power installed onshore the tariff is equal to 7.3 c€/kWh for the first 20 years and 6.1 c€/kWh for the following years. For solar PV, on the other hand, the tariff is divided into three categories based on the installed power: 44.0 c€/kWh ($P < 100$ kW), 41.8 c€/kWh (100 kW $< P \leq 10$ MW) and 23.0 c€/kWh ($10 < P \leq 50$ MW).

Thanks to the incentives of the "*Real Decreto 661*", the photovoltaic systems installed have had an exponential growth, far exceeding the objectives set by the decree. For this reason, a new decree ("*Real Decreto 1578/2008"* [58]) was necessary to regulate the diffusion of this technology. The maximum annual limit of 500 MW was established between 2009 and 2011. In this new decree, the goal will be calculated on the basis of new technological advances. In this decree the systems are divided into two categories, those installed on a lot with urban cadastral reference (buildings, parking lots, etc.), and all the others. The new regulated tariff is equal to 34.0 c€/kWh for plants of the first type (I.1) with installed power of less than 20 MW; equal to 32.0 c€/kWh for plants greater than 20 MW (I.2) and all plants of the second category (II)

Through the "*Real Decreto 1565/2010*" the incentive scheme was reduced again, and in 2013 the FiT was equal to 24.8 c€/kWh for Type I.1, 17.5 c€/kWh for type I.2, for Type II it was equal to 11.5 c€/kWh. In addition, a restriction was placed on the operation of photovoltaic systems. In other words, the incentive rate was no longer paid when the equivalent solar hours reached a certain limit. When this constraint was further reduced, many plants exceeded the corresponding maximum number of hours. So, the FiT was suspended and consequently many plants were no longer profitable. For fixed axis PV systems, the maximum value of solar equivalent hours was 1250 [kWh/kW] until 2013. Finally, in 2012 the FiT incentive system was removed for new plants, not just photovoltaic ones [59].

In 2015, "*impuesto al sol*" came into force in Spain, which is a tax based on the self-consumption of electricity produced by PV systems. The principle with which this tax was enacted was to make the user pay a tax for the use of the grid when the PV systems fail to meet the load [60]. Plants with installed power of less than 10 kW, plants not connected to the grid and systems installed on islands were excluded from the payment. In 2018 through the "*Real Decreto-ley 15/2018*" it was abolished. Furthermore, the Spanish government is implementing actions to encourage self-consumption, in accordance with European directives.

In [61] it is described how also Spain has adopted an auction system for the promotion of renewable sources. In particular, with the "*Real Decreto-lay 23/2020*", it is described how the auctions are based on the remuneration price of electricity. Only small-scale plants or some projects may not participate in these as they are not competitive.

During the first auction, incentives were awarded for over 3 GW of wind and photovoltaic plants. The incentive takes place on the energy produced; in particular, for photovoltaics the average price was 24.5 €/MWh and for wind power 25.3 €/MWh. The installable power is put up for auction and the owners offer the price they wish to receive. In addition, the minimum volume of energy that must be sold is also defined.

In the second auction in 2021 approximately 3.3 GW are made available, of which 600 MW for wind and photovoltaic plants already available, 700 MW for PV systems and 1500 MW for onshore wind.

Germany was one of the promoters of the FiT scheme in Europe, subsequently this mechanism was adopted in many other states, including Spain and Italy. This system has had great results, in fact in all countries the installation of new systems had an exponential growth. During the first years of the incentive, the tariff was very high, on average around 40-50 c€/kWh, this allowed small producers, to develop this technology. Subsequently, many European states have decided to change their incentive system, abandoning the FiT system. Currently, many countries have an auction system. In this way, the installation of new plants is limited by the power quota made available. Furthermore, a competitive system is created to limit the oversizing of the incentive. In developing countries, various policies are being implemented to encourage the development of renewable sources. If we analyse the case of Sri Lanka or the Philippines, is possible to note, how the incentive for each kWh is very similar to that currently guaranteed by some EU countries; however, there are substantial differences with these states. One of the first differences is the cost of installing these technologies. In fact, in highly developed countries that have used incentive systems for several decades, the cost of PV modules and wind generators has dropped drastically. Furthermore, many EU states use other methods in addition to the FiT system, such as the "*Scambio sul Posto*" for Italy or the auction and premium system for Germany.

From the results shown by developed countries, further effort is therefore required to achieve the desired results.

3.2 Definition of economic parameters

To perform an economic analysis, it is necessary to define some parameters that are able to represent the economic feasibility of the project.

One of the main parameters is NPV (*Net Present Value*), it is defined by the Equation 3.6.

$$NPV = \sum_{t=0}^{N=25} \frac{R_t}{(1+i)^t}$$

(3. 6)

R_t represents the net annual economic flow, instead the parameter $(1 + i)^t$ is the term that is used to discount the economic flow of each year. R_t is given by the sum of all cash flows, calculated on an annual basis, it is calculated annually as the sum of all cash flows, both positive and negative. Among the negative flows, the main contribution is represented by the initial investment cost and annual maintenance costs. The positive flows, on the other hand, represent the economic revenues of the project, such as the sale of the energy produced. NPV is calculated over the entire useful life of the project, for the plants considered in this work, a useful life of 25 years is considered. i represents the discount rate at which the investment is carried out.

Another economic indicator calculated is the IRR (*Internal Rate of Return*). IRR represents the discount rate such that the value of the NPV is equal to zero, so when the positive cash flows are equal to the negative ones. This parameter is used to evaluate the profitability of the initial investment, in fact it is possible to define the lower limit of this parameter in order to compare it with the calculated one. The value of the IRR can be compared with the value of the discount rate used in the calculation of the NPV. If the calculated value of the IRR is higher than the discount rate used, then the investment can be profitable. The calculation of this parameter is performed as indicated in the Equation 3.7 and calculated over the entire useful life of the system.

$$\sum_{t=0}^{N=25} \frac{R_t}{(1+i)^t} = 0$$

(3. 7)

It is possible to graphically represent the value of the NPV over the entire useful life of the plant. Note that in the first year the value is negative due to the initial investment cost. From the graph it is possible to see how when the NPV trend intersects the abscissa axis, at that point there is a breakeven point and the positive cash flows is equal to the negative ones. The year in which the NPV is zero is defined PBT (*Pay Back Time*), and it is also an economic parameter to use to evaluate the profitability of the investment. It is possible to graphically show after how many years the system is able to compensate for the initial costs. After this year it is presumed that the plant will be able to generate profit. *Figure 3.1* shows an example of the trend of the NPV, calculated for 25 years, in which the PBT is equal to 13 years.

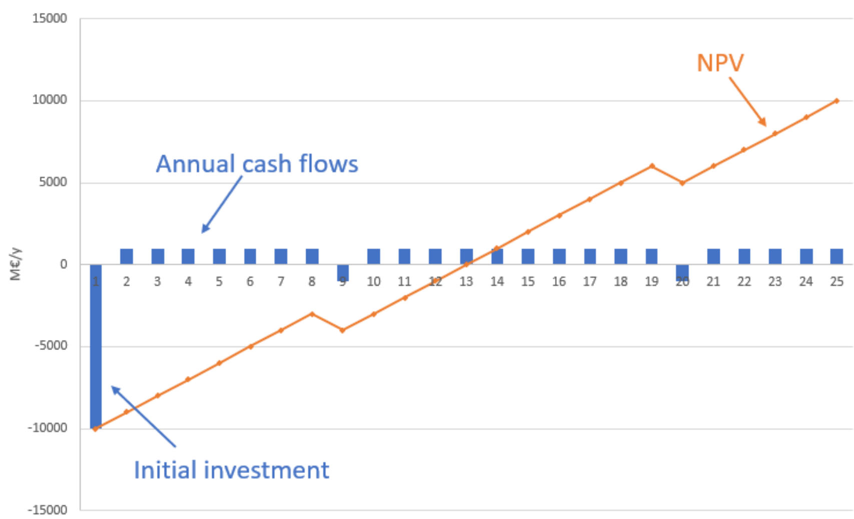

Figure 3. 1 Representation of the NPV trend

Another parameter to be calculated during the economic analysis is LCOE (*Levelized Cost of Energy*). It represents the cost of the unit produced. In the case of production plants, it is defined as the cost of the unit of energy produced such that it is possible to recover the cost of the economic investment. This parameter is very useful for comparing different systems. It is possible to calculate the LCOE value using Equations 3.8.

$$LCOE = \frac{\sum_{t=0}^{25} \frac{I_t + O\&M_t}{(1+i)^t}}{\sum_{t=0}^{25} \frac{E_t}{(1+i)^t}}$$

(3. 8)

To calculate this parameter, it is necessary to know the value of the initial investment, the costs of Operation and Maintenance (O&M) and the annual productivity. Also in this case, the parameter is calculated considering the entire useful life of the plant and discounting the annual economic flows. This parameter is useful for comparing different systems, including those of different technologies.

From the IRENA report on renewable energies [62], it is possible to see how this value has decreased over the years as regards wind and PV systems. For PV systems, the LCOE value decreased from 0.381 $/kWh to 0.058 $/kWh, in the period from 2010 to 2020. In the same period, the LCOE for onshore wind systems decreased from 0.083 $/kWh to 0.041 $/kWh.

These parameters represent estimates on investments and not absolute forecasts, but they are of fundamental importance in the planning phase.

The information in this paragraph refers to the information in articles [63], [6] [15]

3.3 Electricity Price & Demand

Another analysis on which it is possible to make a comparison is that of electricity consumption for Sri Lanka compared to other countries such as Italy, Germany, and Spain. It is also possible to highlight the price for each kWh consumed.

From the data provided by IEA (*International Energy Agency*) the electricity consumption per capita for Sri Lanka is 0.7 MWh/capita per year referring to 2019 [19].

The situation for the developed countries analysed previously is very different. In fact, from the data provided by the IEA, it is noted that annual electricity consumption per capita is much higher than that of Sri Lanka, in particular: for Italy it is equal to 5.2 MWh/capita [64], for Germany 6.6 MWh/capita [65] and for Spain 5.4 MWh/capita [66]. From the data obtained from IEA it is possible to indicate the annual electricity consumption for the residential sector of the four analysed Country. Using the population data of each country it is possible to calculate, with a simple division, the per capita value of the annual electricity consumption for the residential sector. The data of these parameters refer to the year 2019.

In [67] it was shown that Sri Lanka's residential electricity consumption is about 71 kWh per month referring to the year 2017. Only about 10% of household consumers consume more than 120 kWh per month. From the information in [68], it is instead possible to create a more detailed table (*Table 3.7*) by dividing consumers into domestic, industrial, and general consumers and including not only the cost for each kWh consumed, but also the fixed price that is paid monthly by the consumer.

Type of User	Contract Demand	Nominal Tension	Category	Specific cost for kWh [c€]	Fixed cost for Month [€]
Industrial			**Monthly consumption**		
	< 42 kVA	400/230 V	< 301 kWh	4.6	2.6
			> 300 kWh	5.2	
			Time intervals		
	> 42 kVA	400/230 V	18:30-22:30	8.8	12.9
			5:30-18:30	4.7	
			22:30-5:30	2.9	
	-	11 kV	18:30-22:30	10.1	12.9
			5:30-18:30	4.4	
			22:30-5:30	2.5	
General			**Monthly consumption**		
	< 42 kVA	400/230 V	< 301 kWh	7.9	1.0
			> 300 kWh	9.8	
			Time intervals		
	> 42 kVA	400/230 V	18:30-22:30	11.4	12.9
			5:30-18:30	9.4	
			22:30-5:30	6.6	
	-	11 kV	18:30-22:30	10.9	12.9
			5:30-18:30	8.9	
			22:30-5:30	6.2	

Domestic	**Monthly consumption < 60 kWh**		
	0 – 30	1.1	0.1
	31 – 60	2.1	0.3
	Monthly consumption > 60 kWh		
	61 – 90	4.3	0.4
	91 – 120	11.9	2.1
	121 – 180	13.7	2.1
	>180	19.3	2.3

Table 3. 7 Electricity price for different users – Sri Lanka

From the data provided by EUROSTAT [69], it is possible to estimate the price of electricity for EU countries. In this case, consumption is divided into two categories, residential consumers (2500 kWh – 5000 kWh) and non-residential consumers (500 MWh – 2000 MWh). In particular, for Italy the cost is 22.6 c€/kWh, for Germany 31.9 c€/kWh and for Spain 23.2 c€/kWh for residential consumers. For the second category, the prices are respectively 15.8 c€/kWh, 18.1 c€/kWh and approximately 10 c€/kWh. The data that have been provided by EUROSTAT refer to the first half of 2021.

The cost is very different from that of Sri Lanka. In fact, for domestic users, the monthly consumption is 71 kWh and so the cost is equal to 4.3 c€/kWh, much lower than in previous countries. Furthermore, the maximum possible tariff in relation to consumption, is equal to approximately 19 c€/kWh: lower than the residantial rate of Italy, Germany, and Spain.

As can be seen from the previous analysis, the price of electricity is lower in Sri Lanka, however it is necessary to take into account the economic possibilities of the population, that is the ability to meet this expense. The analysis of this type is particularly complex and is influenced by various parameters. As a first approximation, the value of GDP (*Gross Domestic Product*) per capita could be used. This economic indicator provided for each country is used precisely to compare the development of the country. For this analysis, the data were taken from the website "The World Bank" [70] referring to the year 2020. In addition, the data referring to the year 2018, which does not contain the effects of the pandemic caused by Covid-19, were taken on the economy of the countries.

From the information gathered, it is clear that, despite the price of electricity being lower for Sri Lanka, its GDP per capita is over an order of magnitude lower than the EU states.

In [71] an analysis was carried out on Sri Lanka's energy development up to 2046. Starting from 2022, an annual growth of about 5% in electricity demand is expected, reaching 53,7 TWh. This growth is consistent with the data obtained over the last 15 years, in which growth of 4.4% was recorded annually.

	Sri Lanka	**Italy**	**Germany**	**Spain**
Electricity price [c€/kWh]				
Residential	4.3	22.6	31.9	23.2
Non-residential	9.2	15.8	18.1	10.1
Annual Electricity Consumption [MWh/capita]	0.7	5.2	6.6	5.4
Annual Residential Electricity Consumption [TJ]	21809	236117	455540	262730
Population [Million]	21.9	60.1	83.2	47.4
Annual Residential Electricity Consumption [MWh/capita]	0.3	1.1	1.5	1.5
GDP 2018 [$/capita]	4059	34605	47950	30350
GDP 2020 [$/capita]	3682	31714	46208	27350

Table 3. 8 Difference between Sri Lanka and three EU countries for the consumption and price of electricity

Electricity selling Price

To cope with the increase in energy demand for Sri Lanka in the coming years, the cost of electricity is also likely to increase due to the installation of new plants. This trend is confirmed by the details in articles [72] and [73], which show a steady increase in the average electricity selling prices for Sri Lanka. In particular, is reported the average electricity prices of the two large Sri Lankan electricity distributors, CEB (*Ceylon Electricity Board*) and LECO (*Lanka Electricity Company Limited*). In article [72] prices from 2010 to 2014 are shown, in article [73], instead there is a more analysis in which prices from 2010 to 2019 are added, also there is a graph in which the values from 1983 to 2019. From this information it is possible to see how the price of electricity in Sri Lanka is constantly increasing.

Using the graph of the average selling price of electricity in Sri Lanka from 1983 to 2019 reported in the article [73], it is possible to estimate the rate of increase in the price of electricity over the years. *Figure 3.2* shows the values expressed in Sri Lankan Rupees (LKR), while *Figure 3.3* represents the information expressed in c€/kWh. With the graph in *Figure 3.3*, is possible to analyse the rate of increase in prices over the years and not its absolute value, for this reason an exchange rate equal to 0.44 [LKR/c€] was used to convert the values of LKR into €, constant and referring to 29 January 2022 [25].

From this analysis it is possible to note that the average annual increase in the selling price of electricity is 7%, taking the values from 1983 to 2019. Taking into consideration the last 10 years, from 2010 to 2019 the average annual increase is 3%. The years in which, on the other hand, there was the highest percentage increase are 1993-1994 (41%), 2001-2002 (31%) and 2011-2012 (21%).

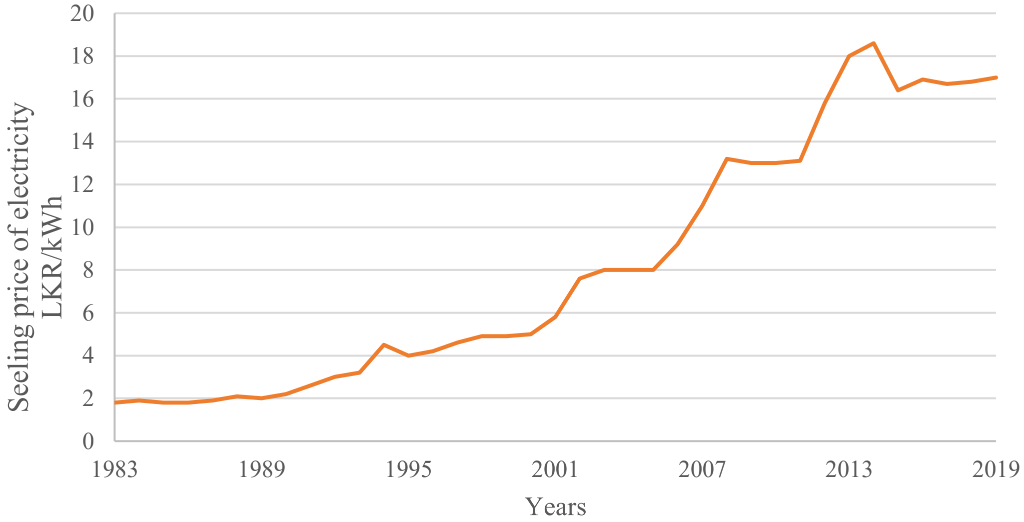

Figure 3. 2 Average selling price of electricity in Sri Lanka [LKR/kWh]

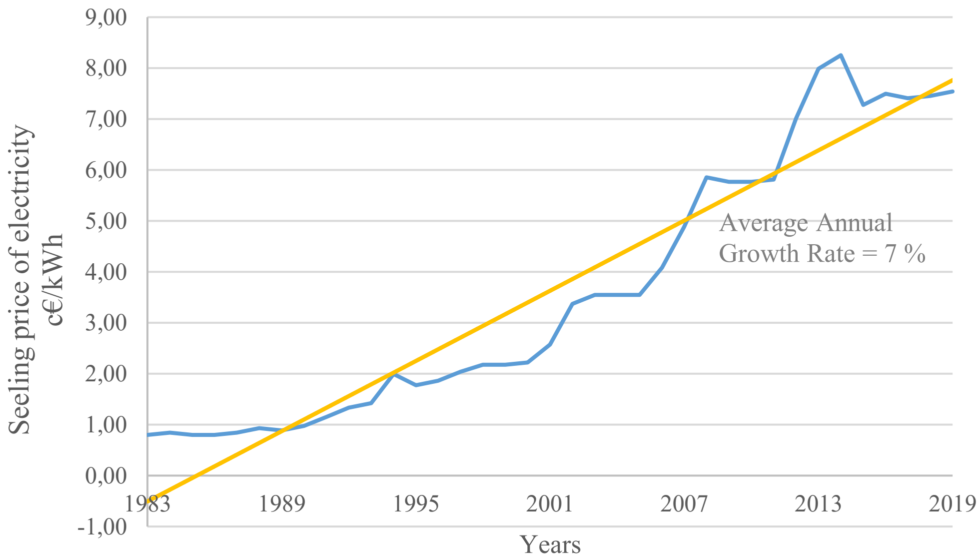

Figure 3. 3 Average selling price of electricity in Sri Lanka [c€/kWh]

Figure 3.4 shows the trends in the price of electricity in three different cases: 1%, 3% and 7%. In this case it was assumed that there is an annual increase in the price of electricity corresponding to the value indicated as a percentage. It can be seen that in the graph there is also a second-order polynomial curve that approximates the trend of the data up to 2019 and provides an estimate of future data with the same trend as the past ones.

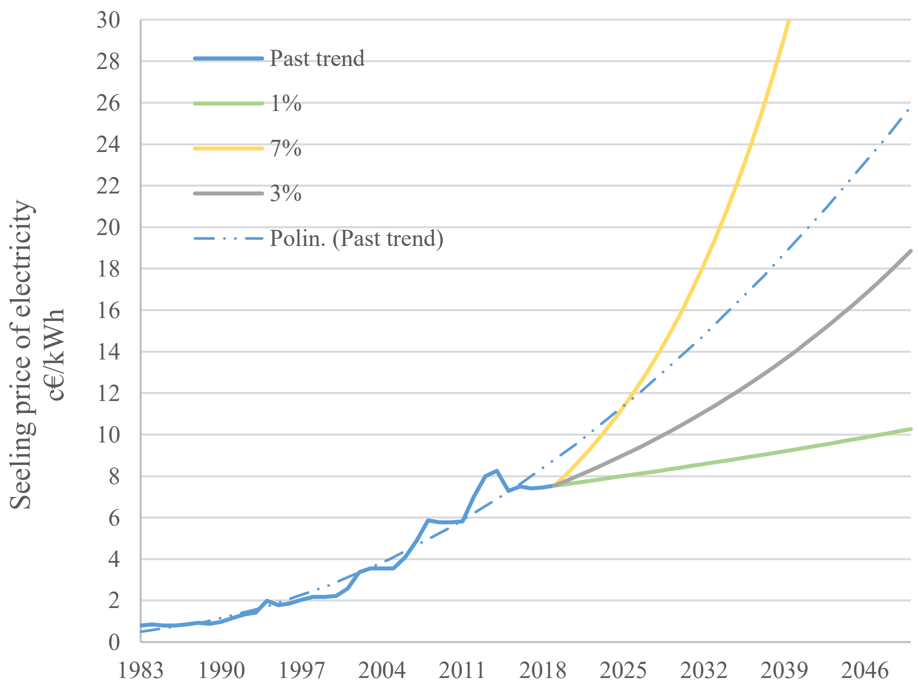

Figure 3. 4 Scenarios of the average selling price of electricity

Electricity Demand

As shown above in the article [71], the increase in demand in the state of electricity Sri Lanka is considered to be the period from 2006 to 2020. Between 2019 and 2020 data, the growth is 2.2%. The data are consistent with the values presented previously in Chapter 2 on Sri Lankan electricity consumption by IEA (*Figure 2.3*)

Within the article [71] the calculation of the forecast of the "*Demand Base Case 2022-2046*" was described, in which the electricity consumption for Sri Lanka was estimated, using demand data from previous years and some variables for the econometric model, such as the Gross Domestic Product, the population and the average price of electricity. In the article, three different scenarios have been identified: "Base Demand Forecast", "High Load Demand Forecast" and "Low Load Demand Forecast". The cases analysed refer respectively to a rapid and slow economic growth of the country, due to the industrial and services sector. In the base case, the average annual growth rate of demand was estimated to be 5.2%, in the High Load case it was 5.5% and in the Low Load case 5.1%. *Figure 3.5* shows the data referring to the 3 selected scenarios, indicating the data of the electricity demand for the period 2006-2020, and representing the data of the three observations.

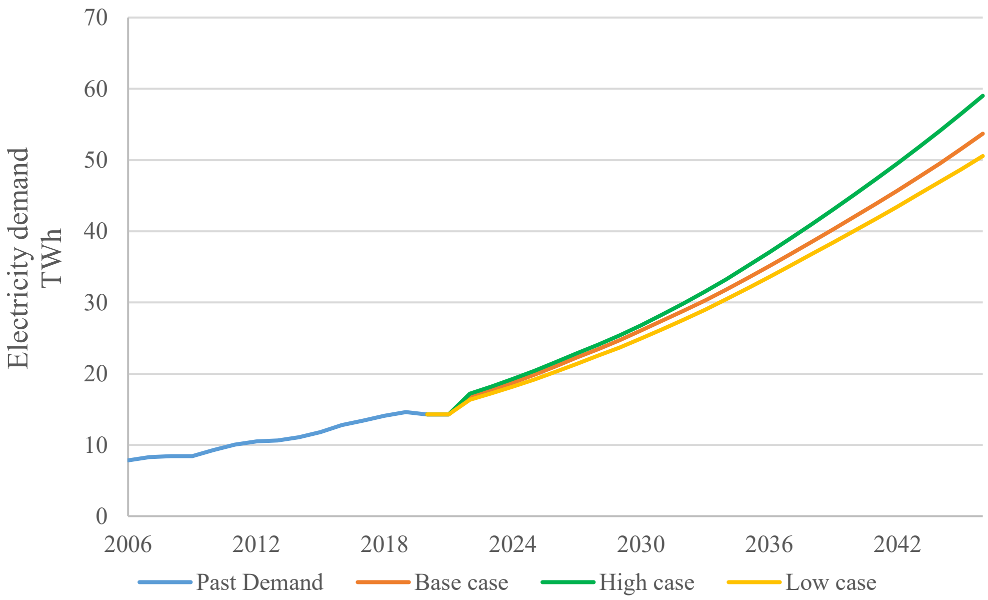

Figure 3. 5 Electricity demand scenarios

3.4 Load profile

In this thesis work, for the calculation of the hourly load of Sri Lanka, in the absence of an hourly profile for this country, information from other countries was used. The available data of the load profile are provided by ENTSO-E [74] and refer to the countries of the European Union.

The average monthly temperatures of the main cities of Sri Lanka were compared with that of European countries on the Mediterranean coast, in particular Italy, Spain, and Portugal. From the temperature data shown in *Figure 3.6*, the climatic conditions of the Mediterranean countries in the winter months are very different from those of Sri Lanka. In order to have an hourly profile available that is as real as possible, it was decided to use only the load data that refer to the summer months. From *Figure 3.6* it is noted that the country with summer temperatures most similar to that of Sri Lanka is Italy. The temperature data are shown for 3 different cities for each country, respectively selected in the north, south and centre of each country and are obtained on the website [75]. To create the annual load, the data referring to the summer months are then repeated for about 4 times in order to obtain an annual profile with 8760 values. Subsequently, to adapt the load of the selected country to that of Sri Lanka, a corrective factor proportional to the annual electricity consumption of Sri Lanka is calculated and referred to the same reference year with which the load data for Italy are provided by ENTSO-E.

T [°C]	Sri Lanka			Spain			Italy			Portugal		
	Jaffna	Kandy	Colombo	Santander	Madrid	Seville	Milano	Roma	Palermo	Porto	Lisbona	Albufeira
January	25,8	23	27,5	10,6	6,3	11,2	3,5	7,7	12,4	9,6	11,6	11,8
February	26,2	24,5	28	10,4	7,6	12,7	5,4	8,4	12,2	10,6	12,8	12,6
March	27,6	25,5	28,9	11,8	10,8	15,5	10	10,9	13,7	12,8	15	13,5
April	29,5	26	29,3	12,7	13,2	17,7	13,9	13,8	15,8	13,8	15,8	14,8
May	30,1	26	29,5	15	17,4	21,4	18,6	17,9	19,4	16,2	18	17,1
June	29,8	24,5	29,2	17,6	22,8	25,4	22,8	22,4	23,3	19	21,2	20
July	29,4	24,5	28,9	19,7	26	28,1	25	25,2	26	20,7	23	22,6
August	29,2	24,5	28,7	20,5	25,8	28,4	24,6	25,6	26,8	20,8	23,5	22,6
September	28,9	24	28,3	18,8	21,4	24,8	20,1	21,3	24,1	19,5	22,2	21,8
October	27,8	24,5	28,1	16,8	15,8	20,6	14,7	17,3	20,9	16,6	18,9	18,5
November	26,6	24	27,7	13,2	10	15,3	8,8	12,7	17,2	13,2	15,1	15
December	26	24	27,5	11,4	7	12,2	4,2	8,7	13,8	10,9	12,4	12,8
Year	**28**	**24,55**	**28,4**	**14,85**	**15,35**	**19,45**	**14,3**	**16**	**18,8**	**15,3**	**17,45**	**16,9**

Figure 3. 6 Average temperatures between cities in Sri Lanka and cities in the EU

From the data provided by ENTSO-E, the annual consumption of this country was calculated with the data referring to the last available year, i.e. 2015. Subsequently, the data on electricity consumption in Sri Lanka referring to the same year was obtained by IEA [19]. The load profile was then adapted with the average consumption of the country.

The difference between the different areas of the country was not considered, in which different conditions arise, due to the presence of large urban centres. It was therefore assumed to consider an aggregate of a high number of users, in order to obtain an averaged profile on the different types of users.

Figure 3.7 shows the load profile referring to a single day obtained from the data of Italy with the methodology just described.

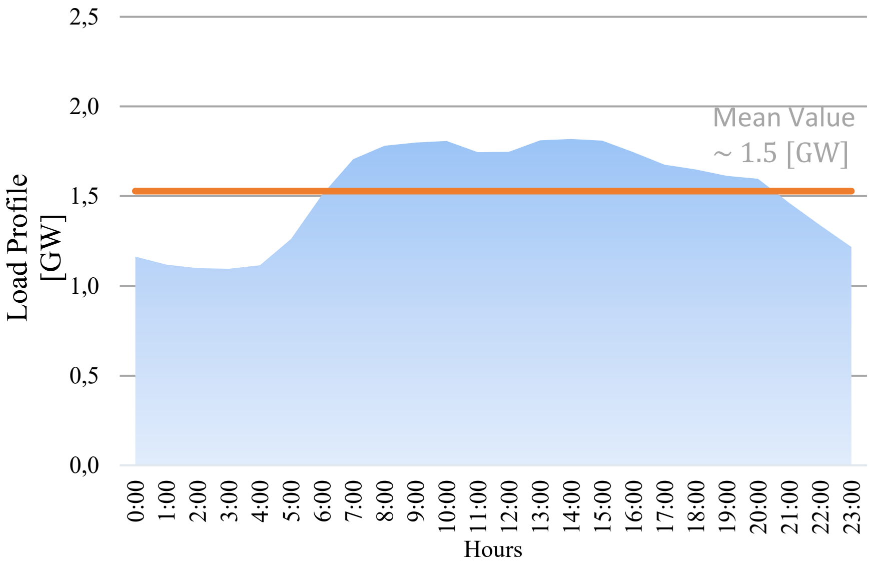

Figure 3. 7 Representation of the hourly profile of a significant day

Is possible to compare this trend with that found in the literature in the articles [73] and [71]. In particular, [73] shows the hourly profile referring to the day 22\09\2015, which represents the day in which the maximum peak was recorded for Sri Lanka in this year. This document contains the hourly profiles referring to the day on which the maximum peak was recorded, reporting the data from 1997 to 2019.

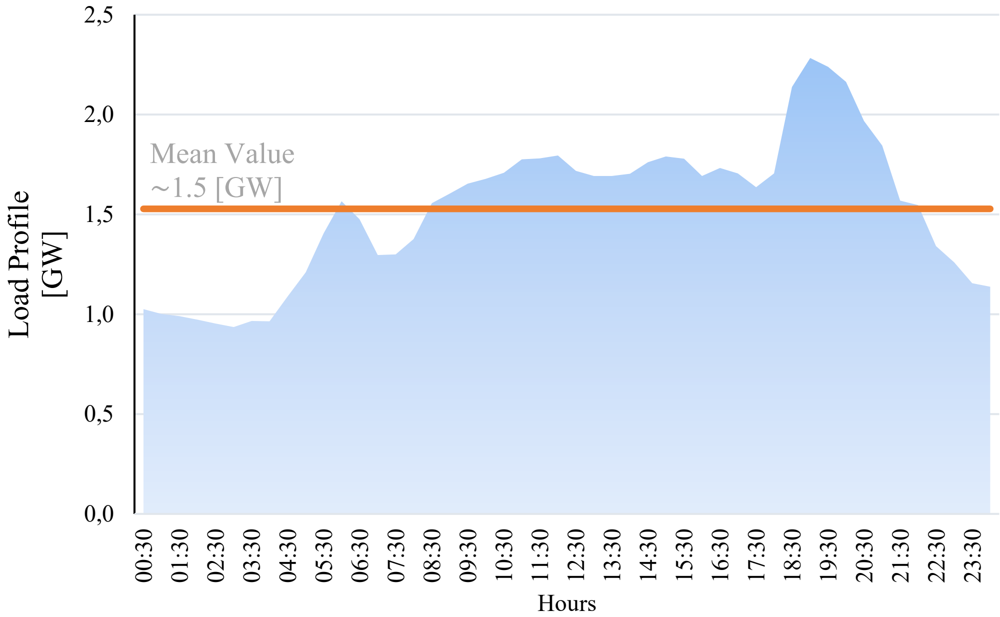

Figure 3. 8 Load Profile of 22/09/2015 in Sri Lanka [73]

Also in the article [71], the trends referring to the days with the maximum peak of electricity consumption are shown. In this case, the data from 2013 to 2020 are shown. *Figure 3.9* is taken from document [71] and shows these trends, in this case it can be seen that the hourly profile has a very similar trend over the years. In particular, the maximum consumption is always recorded in the evening, between 19:00 and 21:00.

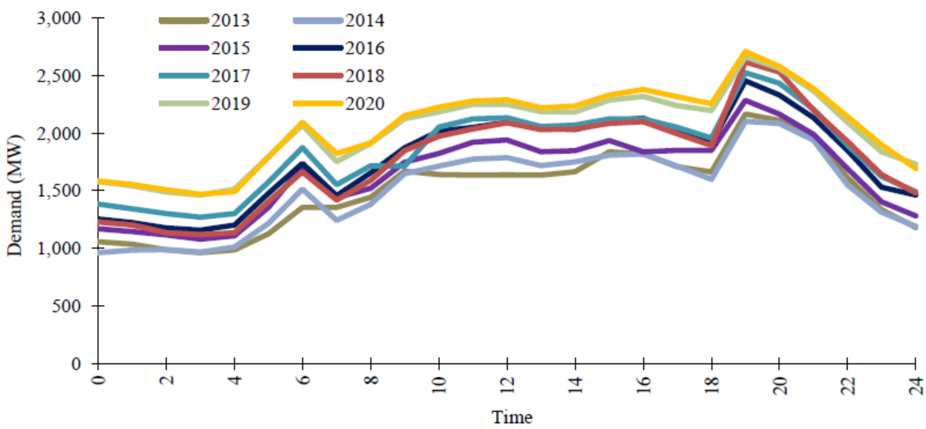

Figure 3. 9 Daily profile in Sri Lanka for different years [71]

From the comparison between the daily load calculated from the data used for Italy and those obtained in the literature for Sri Lanka, some differences can be seen. The average value calculated for the single day is similar to that obtained from the data for Sri Lanka [73] for the same reference year. However, the profile found in the literature has very pronounced peaks at night, and a little variable load for the remaining hours of the day. The profile used in this work, on the other hand, does not show the same trend, but in the absence of further information available, this trend was used for subsequent calculations.

On a representative level, the data of the weekly, monthly, and annual hourly profile calculated with the method just described are reported. As can see, the annual hourly profile referring to the year 2015 does not present any seasonal variation as it is formed by the repetition of hourly profiles referring only to the summer months.

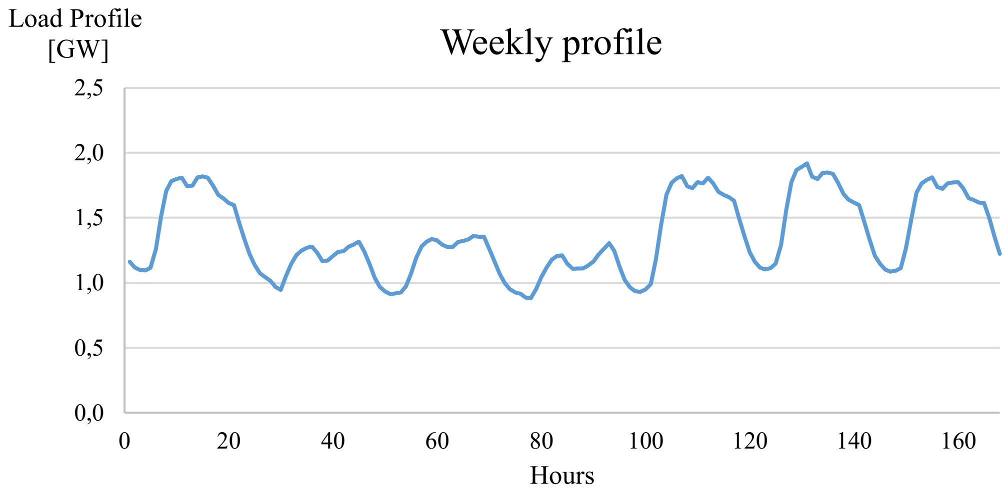

Figure 3. 10 Calculated weekly load profile

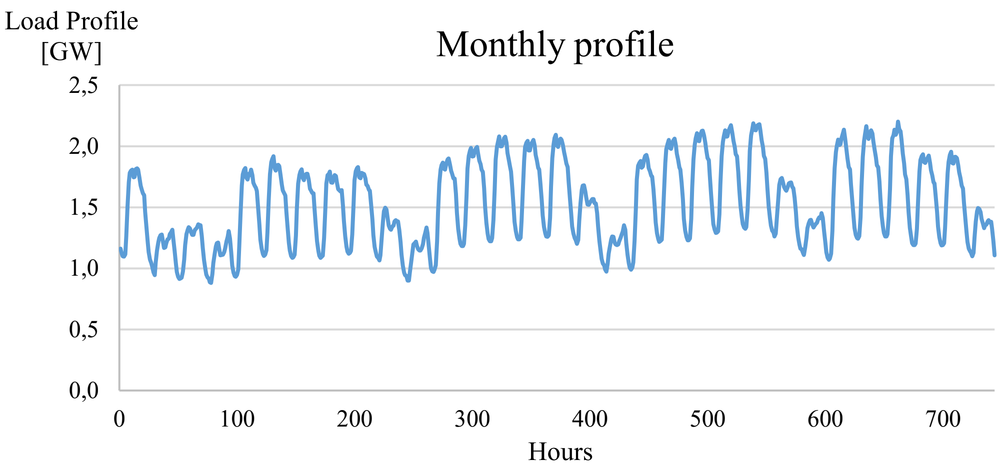

Figure 3. 11 Calculated monthly load profile

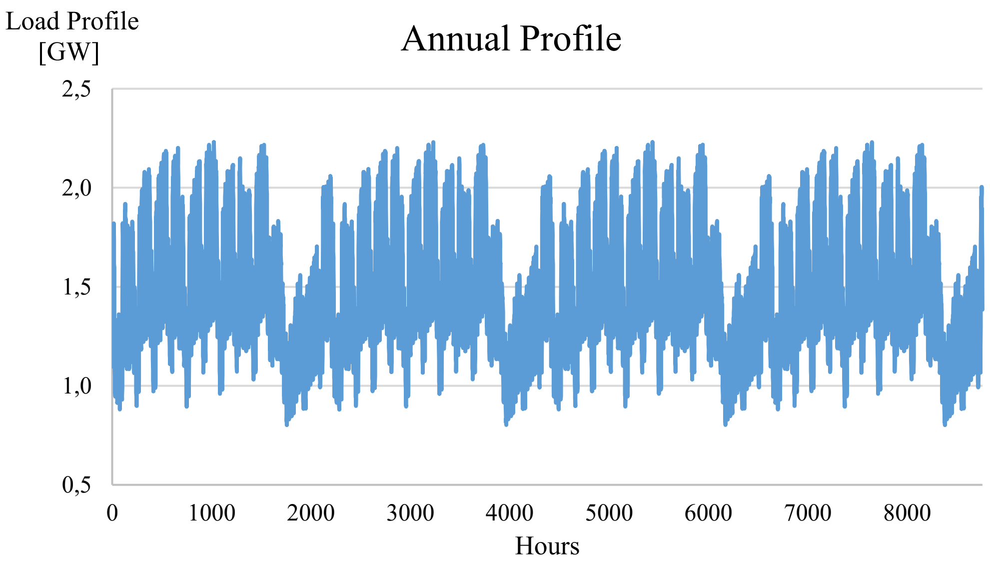

Figure 3. 12 Calculated annual load profile

In this thesis work, an annual increase of 1% for the electrical load was used to consider the effects of future expansion in the coming years

3.5 Financial data

To analyse the potential of installing new plants, the return to the investment is a fundamental parameter to be taken into consideration. To carry out the economic analysis it is necessary to correctly identify the economic flows involved. In the previous paragraph, attention was paid to the energy policies implemented in Sri Lanka in order to encourage these technologies and the electricity price. In this part, the main data used in the economic analysis will be presented, distinguishing between photovoltaic systems, wind generators and storage batteries.

From the information in article [71], to perform the economic analysis in Sri Lanka it is appropriate to use a discount rate of 10%

Solar PV

The cost of photovoltaic systems varies greatly with the size of the system used. The specific price, per unit of installed power, for large production plants is much lower than domestic systems installed on roofs. From the analysis conducted by IRENA [62], it can be seen how the price of these systems has been decreasing in recent years, this is mainly due to the improvement of construction techniques and the use of more performing systems, with higher efficiency. In the analysis of a photovoltaic system, the cost of the PV modules and the inverter covers about 60%. In determining the specific cost of these plants, a very important share is represented by the Balance of System (BoS). It is the set of all components with the exception of the modules. The cost difference between different countries is often generated precisely by the cost of the BoS, which also includes soft costs which account for about 23% [62]. Increasing the installation area could reduce this weight; in addition, the presence of a new market for this technology reduce the soft costs.

The price of the PV modules varies with the type of technology used: the price ranges are between 0.2 \$/W and 0.4 \$/W [62]. The *Table 3.9*, obtained from IRENA information, shows the specific cost of the systems for different countries. In this case, the difference was made between utility-scale power systems (at least 1 MW) and residential systems.

	Utility-scale power plants		Residential power plants	
Countries	$/kW	€/kW	$/kW	€/kW
India	596	527	658	582
China	644	569	746	662
Spain	761	673	1397	1235
Germany	830	734	1609	1422

Table 3. 9 Installation cost of PV system

The global average price is around 883 $/kW for large power plants; on the other hand, for domestic systems, the price ranges from 658 $/kW (India) to 4236 $/kW (California) [62]. Making an average between the various countries an average cost of 1747 $/kW can be assumed. These values are confirmed by some data obtained from a web search for photovoltaic systems in Sri Lanka, by consulting the sites of some suppliers of PV modules.

In [76] an analysis was carried out on the integration of PV modules and storage systems in Sri Lanka. The economic data used in this study are consistent with those shown previously, in particular in the case study panels in Polycrystalline Silicon BP 3225T were selected. The specific cost per kW installed can be calculated as approximately 1721 $/kW and the maintenance cost is 10% of the initial cost.

Wind Turbine

The most used turbines on the market are horizontal axis turbines with 3 blades and upwind technology. The cost of construction of the turbines has a great impact on the total cost of the plant, approximately from 64 to 84% of the total cost, due to the expensive cost of the materials. Over the years, the price of these generators has undergone various trends, due to fluctuating material prices and for the energy policies of the states that encouraged the installation of new plants. Furthermore, the introduction of a new market for this type of technology has affected prices. Over the years, research has designed various technologies, as the height of the rotor or the diameter varies, and consequently the price of the generator has varied. However, a global trend foresees the reduction of the installation cost of these plants from 1987 to 2020, going from 5241 $/kW to 1355 $/kW [62].

The installation price varies a lot according to the country considered; in *Table 3.10* obtained from the information in [62], there is the installation cost for some countries, referring to the year 2020.

Countries	**Installation cost [$/kWh]**	**Installation cost [€/kWh]**
Europe	1515	1335
North America	1403	1236
Other Asia	2472	2179
India	1038	915
China	1264	1114

Table 3. 10 Installation cost of WT generators in IRENA report

In [62] are also indicated the O&M costs for wind farms, which range from 33 $/kW to 56 $/kW.

In the literature, articles that expose data on the costs of wind farms in Sri Lanka have been identified. The information in articles [77] and [78] refers to 600 kW turbines installed in Sri Lanka. The information obtained from these articles, published in 2008 and 2003 respectively, are consistent with the average data presented by the IRENA report. In [79], attention is paid to the costs of micro-wind in Sri Lanka; in this case both the installation and O&M costs are higher than the previous cases.

The collected data are summarized in the *Table 3.11*

	[77]	[78]	[79]
Turbine	NEG Micon	-	Skystream 3.7
Installation Cost [€/kW]	891	-	3367
Installation Cost [$/kW]	1000	1195 – 1325	3778
Power [kW]	600	600	2.4
O&M	1.5 [%]	0.015 [$/kWh]	3 [%]
Interest rate [%]	14	9.5	6
Lifetime [y]	25	-	20
Cost of turbine [$]	600000	-	9887

Table 3. 11 Installation cost of WT generators in literature for Sri Lanka

Battery storage

From the IRENA report [80] the cost of lithium-ion batteries varies between 200 $/kWh and 840 $/kWh. The cost of these systems depends for about 50% on the materials used, and in particular the costs of the cathode are the largest percentage. However, the cost of these systems has decreased over the years. In fact, the use of these technologies in the automotive sector has increased the spread of these systems, improving their performance and reducing costs. The number of cycles is between 500 and 20000 [80].

In [81], a study was carried out on storage batteries integrated into domestic photovoltaic systems, thus referring to a single house, in Sri Lanka. The cost of lithium-ion batteries is around 350 £/kWh, lead-acid batteries between 100 and 160 £/kWh. In addition, this article contains information from some suppliers of these technologies, like Tesla and LG.

The *Table 3.12* shows the main information obtained for this type of technology in the literature and compared with the prices shown by a web search for Sri Lanka [82].

	Type of battery	**Specific cost [€/kWh]**
Tesla POWERWALL **[81]**	Lithium-ion	410
LG CHEM **[81]**	Lithium-ion	410
Trojan SIND 04 2145 **[81]**	Flooded/wet	120
Ceylon eco solar **[82]**	Lithium-ion	480
IRENA **[80]**	Lithium-ion	180-710

Table 3. 12 Installation cost of battery storage system

The information collected in the previous articles refers only to the cost of the battery, however, for its correct operation, the batteries are integrated into a *Battery Management System* (BMS). Thanks to this system it is possible to monitor the operation of the battery. In addition, the BMS is also able to improve battery performance, as it keeps the system under control by calculating the battery load status [83]. In [84] there is a study conducted on the costs of different technologies for storage batteries; for Li-Ion batteries, the cost of the DC side battery including the BMS is around 325–700 $/kWh.

Chapter 4

4 Case study: PV, Wind Turbines and storage optimal sizing in Sri Lanka

This chapter shows the results of the planning analysis performed of the case study of Sri Lanka. The goal is to identify the optimal size of the generators and the capacity of the storage system, in order to maximize the objective function, in particular, the energy self-sufficiency and the maximum economic return on investment.

First to performing these assessments, it was needed to perform a resource analysis of the selected sites, in order to identify the distribution of resources.

Maximization of self-sufficiency was performed both on the whole country and locally on some regions. In this case, the sensitivity analysis was also performed for the selected sites. For the economic return on investment, the parameters to be maximized are the NPV and the IRR.

To perform the planning analysis and identify the optimal size of the generators and the storage system, it is necessary to exploit the information obtained in the previous chapters. In particular, in *Chapter 2* some possible suitable sites for the installation of photovoltaic and wind generators have been identified. *Chapter 3* contains some useful information for the planning phase. In particular, the installation costs of the systems, the operation and maintenance costs and the discount rate applied to the investment were indicated. In addition, the prices of self-consumed electricity and the selling price for Sri Lanka were indicated. Before starting the different simulations it is necessary to summarize the main data used, which are shown in *Tables 4.1* and *4.2*.

Financial data input			
	PV system	WT system	Storage system
Installation Cost	883 [$/kW]	1355 [$/kW]	460 [$/kWh]
O&M Cost	3,5 [$/kW/y]	0,0006 [$/kWh/y]	
Discount rate - i	10%	10%	

Table 4. 1 Financial data for RES systems

Electricity price	
Electricity selling price	0,086 [$/kWh] for both wind and photovoltaic systems
Self-consumed energy	0,11 [$/kWh] for general users

Table 4. 2 Electricity price used for planning analysis

Furthermore, an annual increase of 1% of the electrical load of Sri Lanka has been considered in this thesis.

4.1 Simultaneity between solar and wind source

In this section, it was analysed the simultaneity that exists between the solar source and the wind one. This analysis was performed through the use of the RES_tool program. The analysis was performed for all the sites selected in *Chapter 2*.

As expressed in *Subsection 1.2*, one of the techniques used to increase the level of self-sufficiency is the installation of generators with different source, such as photovoltaic and wind power system. For example, the photovoltaic system could satisfy the daily loads, while the wind one the night users. However, this analysis requires the correct sizing of the systems and an analysis of the source profiles. If, for the selected site, the irradiance and the wind have similar profiles, the use of the two types of generators could be inconvenient. Moreover, the simultaneous production of the two generators could cause problems to the distribution grid.

Table 4.3 shows some indicators to analyse the simultaneity of the sources.

	Hours / year							
	PV	Wind	PV ∩ Wind	Only PV	Only Wind	PV ∪ Wind		No prod
Site #1	4115	7340	3567	548	3773	7888	90%	10%
Site #2	4094	8408	3883	211	4525	8619	98%	2%
Site #3	4091	7340	3549	542	3791	7882	90%	10%
Site #4	4090	6599	3418	672	3181	7271	83%	17%
Site #5	4140	8168	3806	334	4362	8502	97%	3%
Site #6	4113	8401	3898	215	4503	8616	98%	2%
Site #7	4099	6599	3432	667	3167	7266	83%	17%
Site #8	4100	7445	3660	440	3785	7885	90%	10%
Site #9	4111	7932	3782	329	4150	8261	94%	6%
Site #10	4116	8511	3933	183	4578	8694	99%	1%
Site #11	4116	7205	3669	447	3536	7652	87%	13%

Table 4. 3 Simultaneity analysis between solar and wind sources

The first two columns represent the number of hours in which the generators, respectively photovoltaic and wind system, could be in production, regardless of the presence of the other generators. The third column instead reports the annual hours in which the simultaneity of the source occurs. The fourth column indicates the number of hours in which only the photovoltaic system è was activated, the fifth was referred the wind system. Finally, the sixth column indicates when at least one of the resources was present. The value was also expressed as a percentage of the total annual hours, while its complement represents the percentage of hours in which there was no production. The percentage value of the seventh column represents the maximum limit that can be reached for self-sufficiency without storage.

It should be remembered that the presence of the resource is not the same as saying that there is production, but it could happen that, even if the resource was present, the generator could be not in production. For example, for the photovoltaic generator, it is in operation when the irradiance is higher than the limit to activate the inverter. For wind turbines, on the other hand, the productivity depends on the cut-in and cut-off speed of the turbine.

From *Table 4.3* it can be seen that site #2 has a high number of production hours, equal to 98%. This result is reliable from the analyses in *Chapter 2* on the suitable installation sites. In fact, site #2 was selected for simultaneous installation of both a photovoltaic and wind power system. Sites #5 #6 and #10 also have a high percentage of availability, even reaching 99%. Sites #4 and #7, on the other hand, have the highest percentage of no-productivity, 17%. From this analysis, it can be seen that all the sites analysed show very high values of production hours, mainly due to the presence of the wind source and the solar resource has a low variation in the analysed sites.

Figures 4.1 and *4.2* represent the monthly data reported for site #2.

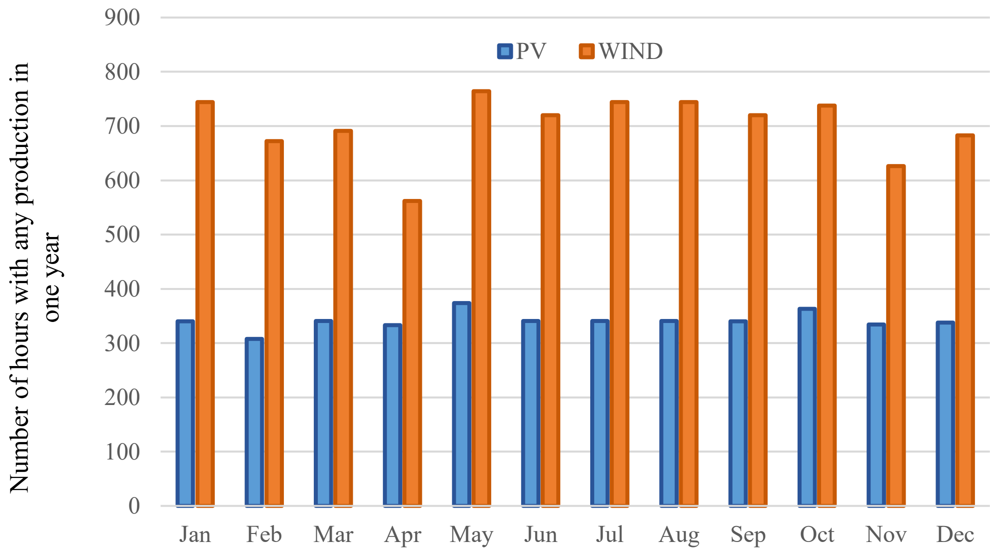

Figure 4. 1 Monthly resource hours of PV and wind systems for Site #2

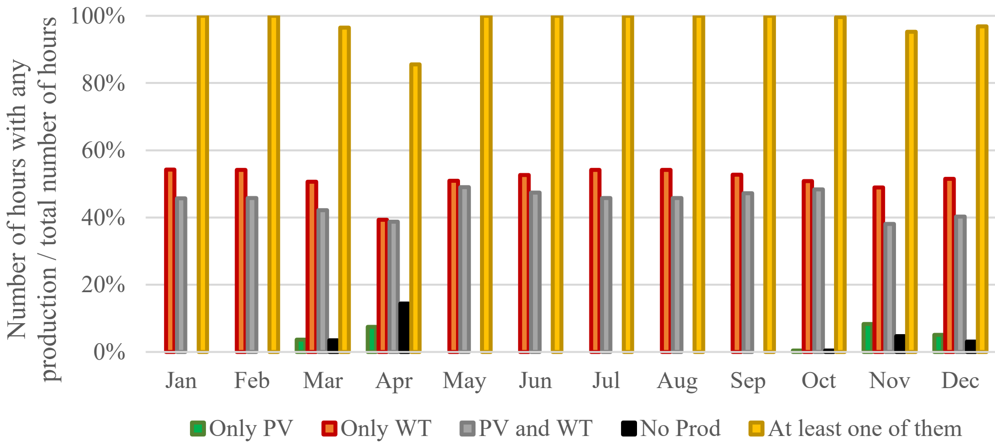

Figure 4. 2 Availability of resources for Site #2

The graphs show how the wind source has a high number of production hours. Considering the production hours of only the wind source, the number of hours is greater than 50% of the total number of hours. April is the month in which wind availability is lower than the other months, this month also reaches the maximum of no-productivity hours equal to about 13%. The percentage of simultaneity is about 50% and reaches its maximum in the month of May when there is also the maximum availability of the solar source. Also note that in the months of January, February, June, July, August and September, the number of hours in which at least one resource is present is the maximum possible respect to the total number.

The simultaneity analysis is very important in the planning phase. In the article [85] there is a study on the analysis of the simultaneity of solar and wind resources for the development of hybrid systems and for the identification of possible suitable installation sites. Simultaneity is based on the concept of synergy and complementarity. Synergy is when resources reaches peak at the same time: high synergy values are useful for systems that have to meet electrical load peaks. Complementarity occurs, on the other hand, when the peak of one resource corresponds to the minimum of the other and vice versa. Therefore, having high complementarity values can reduce the installed capacity because the systems operate at different times.

The document focuses on both temporal and spatial simultaneity. The temporal one relates to technical hybrid systems, i.e. when the systems are installed in the same site. The spatial one, on the other hand, is related to economic hybrid systems which therefore only share economic aspects.

In the article, the simultaneity analysis was focused on India. The analysis was based on three models thanks to the use of statistical matrices and through the use of corrective coefficients. The results show how the regions of the west coast of India show high values of resource complementarity; on the other hand, the resources of the areas of the north-eastern and western coasts of the country present a slight synergy.

It was therefore noted how a careful analysis of the simultaneity of resources can be helpful in identifying possible installation sites and for the study of different plant configurations.

4.2 Resource analysis

Following the simultaneity analysis, the analysis of wind and solar resources was performed for site #2, with the use of the “heat map”. Through this graphic representation it is possible to represent the meteorological data, in which each value was associated with a colour based on its importance within a hierarchical scale.

The simulations on the productivity of photovoltaic and wind power plants were performed with 1 MW plants, both for PV and WT systems. The size of the plant used to calculate the productivity in this paragraph is not important because the objective is to analyse whether there is a predominance of one resource over the other and not their absolute value.

Analysing the data of the irradiance of site #2 from 2005 to 2016 (*Figure 4.3*) it is possible to note how this source slightly changes according to the selected year, in fact in 2006 the annual irradiance is equal to 1592 [kWh/m^2] and in 2014 is 2198 [kWh/m^2]. Instead, it should be noted that there is not a high difference in irradiance between the different months of the year. Even the mean temperature (*Figure 4.4*) between the different months of the year has a low variation. This is presumable, considering the equatorial climate of the country, that there is not much difference between the climatic data of the different seasons.

Irradiance [kWh/m^2]	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Jan	130	126	170	165	187	185	152	195	164	190	195	159
Feb	157	130	191	183	198	185	153	172	161	194	179	161
Mar	163	154	224	180	213	212	202	219	200	214	214	171
Apr	136	153	177	180	185	195	190	187	196	198	199	156
May	159	126	203	196	174	167	200	199	168	188	181	107
Jun	116	143	153	162	173	170	186	169	159	176	179	128
Jul	118	123	180	176	191	176	174	191	175	192	181	132
Aug	155	136	180	178	191	182	184	183	204	190	184	129
Sep	133	144	165	206	184	186	190	180	170	182	155	127
Oct	117	127	168	178	207	191	190	184	198	181	183	166
Nov	109	122	179	163	122	157	149	160	183	149	153	121
Dec	130	108	153	179	147	141	147	152	145	144	154	149
Year	1623	1592	2144	2148	2172	2145	2116	2194	2122	2198	2157	1704

Figure 4. 3 Annual irradiance for Site #2

Temperature [°C]	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Jan	26,0	25,1	25,8	25,5	25,7	26,0	24,9	25,7	25,8	25,5	26,0	26,8
Feb	26,7	26,1	26,1	26,1	26,0	26,6	25,5	25,8	26,1	26,2	26,0	26,8
Mar	27,4	26,9	26,8	26,0	26,8	27,5	26,4	27,0	26,9	27,2	27,0	27,9
Apr	27,7	27,6	27,1	26,9	27,5	27,8	26,9	27,2	27,9	27,4	27,4	28,2
May	27,5	27,4	27,7	27,0	27,2	27,6	27,0	27,7	27,4	27,5	27,5	27,9
Jun	27,4	27,4	27,1	27,2	26,8	27,0	27,4	26,9	26,5	27,6	27,7	27,5
Jul	26,9	27,2	27,0	26,7	27,1	27,0	26,8	27,1	26,5	27,2	27,2	26,9
Aug	27,1	26,9	27,0	26,8	26,7	26,8	26,8	26,7	26,5	26,7	27,0	27,0
Sep	26,9	26,8	26,8	27,3	27,0	26,7	27,1	26,7	26,6	26,5	26,7	26,9
Oct	26,9	26,7	26,3	26,9	26,8	27,0	26,9	26,3	26,4	26,4	26,6	26,7
Nov	25,9	25,8	26,2	26,4	25,9	25,9	26,4	26,1	26,5	26,1	26,7	26,2
Dec	25,8	25,9	25,5	25,8	25,7	25,4	26,2	25,7	25,6	25,8	26,4	26,1
Year	26,8	26,7	26,6	26,6	26,6	26,8	26,5	26,6	26,6	26,7	26,8	27,1

Figure 4. 4 Ambient temperature for Site #2

Figure 4.5 shows the mean wind speed data. In this case it should be noted that this values is very high, mainly in the summer months, with values reaching 9.3 m/s.

Wind speed [m/s]	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Jan	5,9	6,4	7,6	5,5	6,8	6,0	5,5	5,7	6,2	6,1	5,8	5,6
Feb	6,3	6,3	5,3	4,6	4,7	6,5	4,5	6,1	5,2	6,6	6,0	5,7
Mar	4,4	3,9	4,0	3,6	2,6	4,4	3,6	3,4	4,1	6,6	5,2	4,2
Apr	3,4	4,9	3,7	4,5	5,0	4,0	4,6	4,4	4,1	4,0	2,8	3,3
May	7,7	7,8	7,9	8,3	8,6	7,1	7,8	8,8	8,3	6,7	6,9	6,7
Jun	9,5	8,5	8,2	8,1	9,2	8,5	8,7	9,2	9,3	8,9	8,1	9,4
Jul	9,1	9,1	8,5	8,8	8,4	7,6	8,9	9,1	8,8	9,2	9,1	8,5
Aug	8,4	8,2	8,5	8,0	8,7	9,0	8,6	8,6	8,4	8,6	8,1	9,3
Sep	9,0	8,0	8,2	7,5	8,8	7,3	8,5	8,4	8,7	8,0	7,7	9,0
Oct	7,1	4,7	7,2	4,5	4,8	7,6	5,5	5,4	7,6	4,9	4,4	7,2
Nov	4,2	3,3	3,5	3,6	4,1	3,8	4,6	2,9	3,2	5,1	3,9	3,9
Dec	4,8	7,2	5,8	5,3	4,9	5,1	4,9	5,5	5,0	4,6	5,3	4,1
Year	6,7	6,5	6,5	6,0	6,4	6,4	6,3	6,5	6,6	6,6	6,1	6,4

Figure 4. 5 Mean wind speed for Site #2

Analysing the production data obtained, it was noted that the production of the wind source for the selected site is more than three times higher than the solar one. *Figure 4.7* shows the producibility data for 12 years, from these data it can be seen how the production by the wind system is little variable over the years. It is possible to calculate the variability value, as the ratio between the standard deviation and the average value calculated by the RES_tool program. For the wind system, the annual variability is 3.6%. On the other hand, by analysing the monthly profiles of the year 2005 (*Figure 4.6)*, it can be seen that there are very different production values between the various months, in particular in the winter months and in the month of April, production is less than half compared to that of the summer months. The production of the solar source, on the other hand, shows very small variations between the different years and during the various months of the year. These data were confirmed by the previously analysed data of irradiance and wind speed. In fact the values of the irradiance are very similar between the various months, the values of the wind speed instead show considerable differences. The production of wind generators is highly dependent on wind speed, as shown in *Paragraph 1.4.2*, for this reason there is a strong monthly difference between the various months of the year.

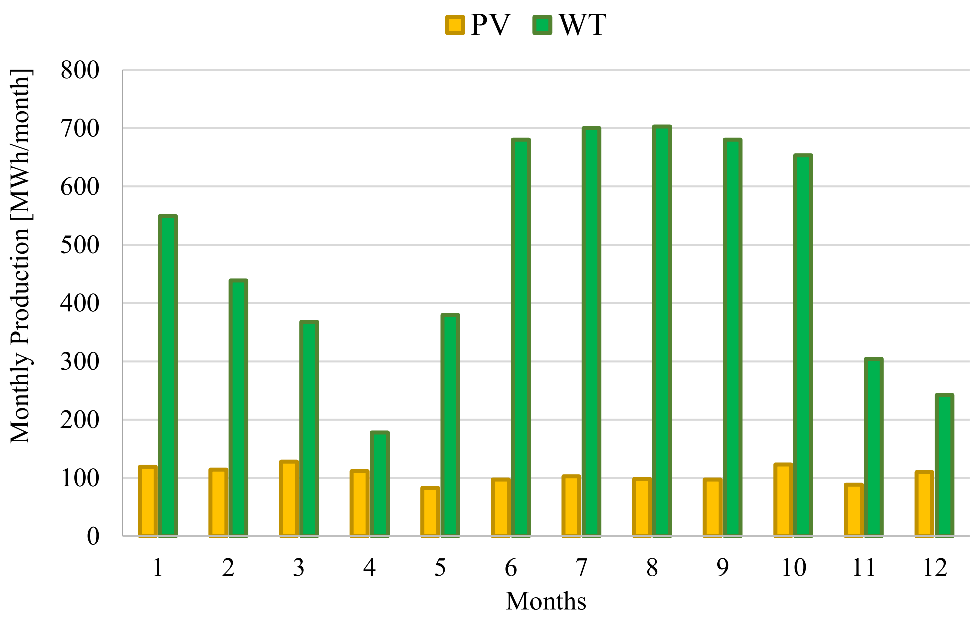

Figure 4. 6 Monthly production of the photovoltaic and wind power plant for Site #2

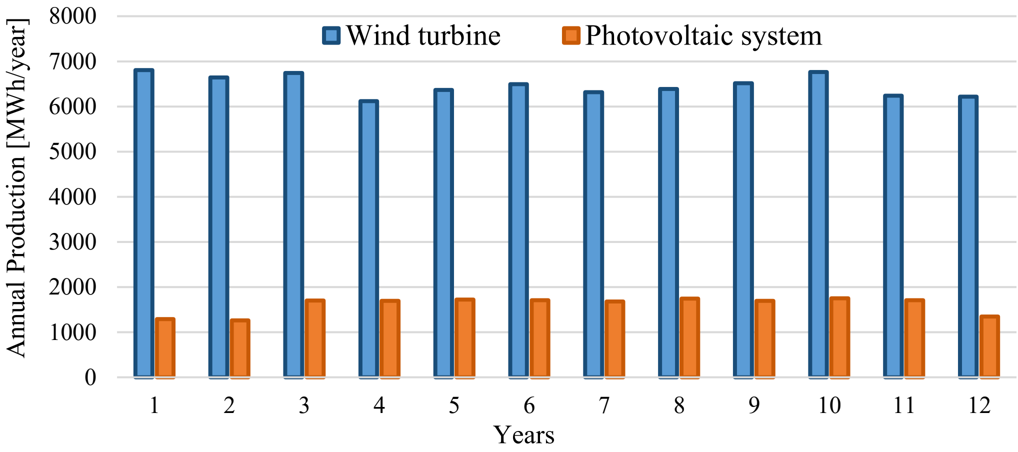

Figure 4. 7 Annual production of the wind and the photovoltaic system, Site #2

Remember how the data shown refer to a chosen plant configuration in such a way as to show the difference between the production of photovoltaic and wind systems. Note how the latter have much higher productions than that of photovoltaic systems. For this reason, greater attention will be paid to the wind source in subsequent analysis.

4.2.1 Wind resource analysis

As shown in the previous paragraph referring to site #2, the wind resource is predominant over the solar one, presenting mean wind speeds higher than 6 m/s. Furthermore, the production of the photovoltaic system has a low annual and monthly variation.

In this paragraph, was analysed if, even for the other selected sites, there is a great diffusion of this resource and then, analyse the characteristics of the conversion technology into electricity to better exploit this resource.

To analyse the wind resource, the main parameter to consider is the mean wind speed, as productivity is highly dependent on this parameter. *Table 4.4* shows the mean wind speeds from 2005 to 2016, for all the sites analysed. As can see, the sites with the fastest speeds are site #2 and site #10. Within *Table 4.4*, the darker areas refer to the sites selected for the installation of wind farms, the lighter areas instead to the installation of PV generators, as also shown in *Table 2.2* in *Paragraph 2.2.4*.

Mean Wind Speed	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Site #1	3.5	3.5	3.5	3.3	3.5	2.5	2.8	2.8	2.7	2.3	2.6	3.6
Site #2	6.7	6.5	6.5	6.0	6.4	6.4	6.3	6.5	6.6	6.6	6.1	6.4
Site #3	3.5	3.5	3.5	3.3	3.5	1.6	1.6	1.5	1.4	1.3	1.4	3.1
Site #4	3.3	3.3	3.2	3.1	3.3	3.6	3.6	3.3	3.3	3.0	3.0	3.4
Site #5	5.1	5.0	5.2	4.9	5.2	5.2	5.4	5.3	5.7	5.4	4.9	4.0
Site #6	5.6	5.6	5.7	5.6	5.7	3.8	4.1	3.9	3.8	3.5	3.5	4.5
Site #7	3.3	3.3	3.2	3.1	3.3	4.2	4.3	4.0	4.0	3.8	3.7	6.7
Site #8	4.1	4.1	4.1	4.0	4.2	4.5	4.8	4.8	4.7	4.3	4.3	4.5
Site #9	4.5	4.6	4.5	4.5	4.7	5.1	5.5	5.5	5.5	5.1	5.3	6.2
Site #10	6.3	6.5	6.4	6.5	6.5	5.2	5.6	5.7	5.7	5.4	5.7	6.2
Site #11	3.9	3.8	3.8	3.6	4.0	4.1	4.3	3.9	3.9	3.7	3.5	4.2

Table 4. 4 Annual mean wind speed for suitable sites

The mean wind speed data for sites #2 #8 #9 and #10 are shown, showing the monthly average values referring to the last available year, 2016.

	Site #2	Site #8	Site #9	Site #10
Jan	5.6	4.3	6.6	6.6
Feb	5.7	4.0	6.0	6.0
Mar	4.2	2.8	4.7	4.7
Apr	3.3	2.3	4.3	4.3
May	6.7	4.5	6.5	6.5
Jun	9.4	6.6	8.1	8.1
Jul	8.5	5.8	6.8	6.8
Aug	9.3	6.1	7.1	7.1
Sep	9.0	6.2	7.2	7.2
Oct	7.2	4.1	4.9	4.9
Nov	3.9	3.3	5.9	5.9
Dec	4.1	3.9	6.3	6.3

Table 4. 5 Monthly mean wind speed for Sites #2, #8, #9 and #10

As can be seen from *Tables 4.4* and *4.5*, the mean wind speeds are very high. *Figure 4.8* shows the speed distributions referred to sites #2, #9 and #10; site #8 was not represented because it has wind distributions similar to those of site #9. The realization of this diagram was carried out as the method described in P*aragraph 1.7.2*. With this method, point values were referred to discrete wind speeds, within the graph of *Figure 4.8* the continuous lines were represented for a simple graphical visualization.

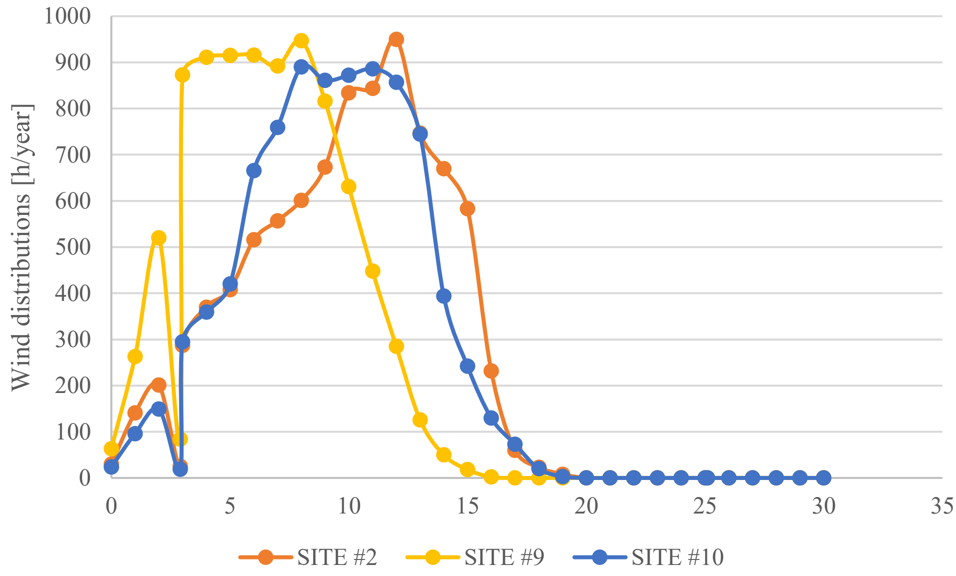

Figure 4. 8 Representation of the wind distribution for Sites #2, #9 and #10

As can be seen from *Figure 4.8*, there is a more concentrated wind distribution at wind speed between 4 and 9 m/s. Through the RES_tool various simulations were performed for the previously selected sites, to analyse how the choice of a turbine can affect the productivity. For this analysis, the key parameter that will be analysed is the Specific Annual Production expressed in MWh/MW. The productivity calculation was performed by reporting the wind speed data, for the various selected sites, to 2016. *Table 4.6* shows the results of this simulation, as can be seen for all the sites analysed, the most performing turbine is the Gamesa G114-2000kW IIA/IIIA, present within the RES_tool. It was analysed how the Specific Annual Production varies between the different turbines, in this case the turbines with lower rated power could not have performance values similar to those with higher power turbines. For this reason the following turbines have been added to the RES_tool programm: VESTAS V150-4.0, VESTAS V90-3MW and Hitachi HTW 2.0-80, obtaining results similar to those of the most performing turbine. Besides the nominal power data, the turbine cut-in speed data was also analysed: as can be seen from *Table 4.6*, the WT Gamesa G114-2000kW IIA/IIIA has a lower cut-in speed than, for example, the VESTAS V90 turbines. Finally, it should be noted how the VESTAS V150-4.0 turbine, with cut-in speeds equal to those of the Gamesa, is able to achieve similar performance and the difference between the two technologies is very small. These results are consistent with the data shown in *Figure 4.8* where it is noted, as previously described, that the wind distribution shows very high values at wind speed between 4 and 9 m/s.

		Nominal Power [MW]	Cut-in speed [m/s]	Specific Annual Production [MWh/MW]				
1	VESTAS V 150 - 4.0	4	3	6713	3641	4256	6558	II
2	VESTAS V 90 3 MW	3	4	4998	1857	2296	4521	
3	LTW101 2500_kW IIIA+	2.5	3	6022	2715	3270	5682	
4	LTW101 3000_kW IIIA+	3	3	5489	2296	2783	5076	
5	Hitachi HTW2.0-80	2	4	5573	2284	2787	5159	
6	LTW77 800_kW IIA/IIIA	0.8	3	6609	3510	4112	6428	
7	Vestas V90-2000_kW IIA	2.03	4	5858	2536	3073	5490	
8	Gamesa G114-2000kW IIA/IIIA	2	3	6803	3798	4412	6682	I
9	ENERCON E-82 E-2 IIA	2.05	3	5692	2396	2915	5293	
10	Nordex N117 Gamma IIIA	2.4	3	6600	3478	4084	6415	III
11	W2E 100/2MW IIIA	2.05	3.5	6091	2777	3342	5770	
				SITE #2	SITE #8	SITE #9	SITE #10	

Table 4. 6 Specific annual production for turbines with different characteristics

Figure 4.9 shows the wind distribution referred to the year 2016 for site #2 and the power curve of the turbine with the highest Specific Annual Production value.

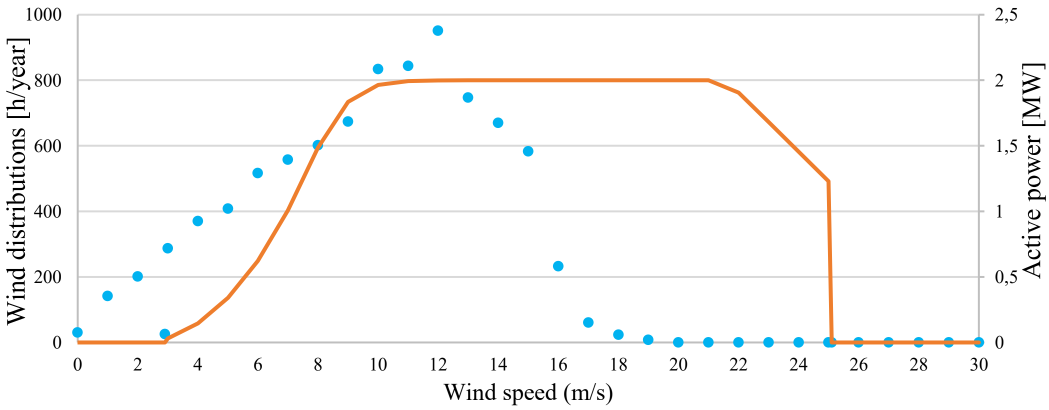

Figure 4. 9 Representation of the wind distribution and power curve of the turbine with higher productivity for Site #2

4.3 Maximization of self-sufficiency

The first objective was to analyse the self-sufficiency of Sri Lanka. In these simulations, the electrical load used refers to the entire nation and the exchanges with the grid by the plant represent exchanges with neighbouring foreign countries. In this case, site #2 was selected for the installation of this plant.

First to analyse how it is possible to maximize self-sufficiency, some graphs of some significant days are shown, in order to analyse the exchanges with the grid and the production profiles respect to the load.

Figure 4.10 represents a day with clear climatic conditions, in fact; from the generation profile of the photovoltaic system it is well distributed throughout the day. In the early hours, from 00:00 to 4:00, the energy production by the wind power plant is higher than the load, in this case the storage battery charge, which will be discharged in the following hours. To compare this system also considering the exchanges with the grid, is possible to compare the graphs in *Figures 4.10* with *Figure 4.11*. When the photovoltaic system was activated, it together with the wind system satisfies the load. As can be seen from the graphs, the generation is higher than the load, at this time the charge of the electrochemical storage was started again. When the storage system has reached its maximum capacity, the excess energy produced will be fed into the grid, and so exchanged with neighbouring countries. In *Figure 4.11*, starting from 9:00 the injection of electricity into the grid begins, but this value was limited to 1 GW. When the photovoltaic system is not able to produce electricity and the wind system is unable to fully satisfy the load, it is therefore necessary to use also the storage battery. Is possible to note how the wind power plant is in production for the whole day, producing energy that satisfy most of the electrical load. It should also be noted that on this day there is no need to absorb electricity from the grid; so, the system is able to fully satisfy the load throughout the day.

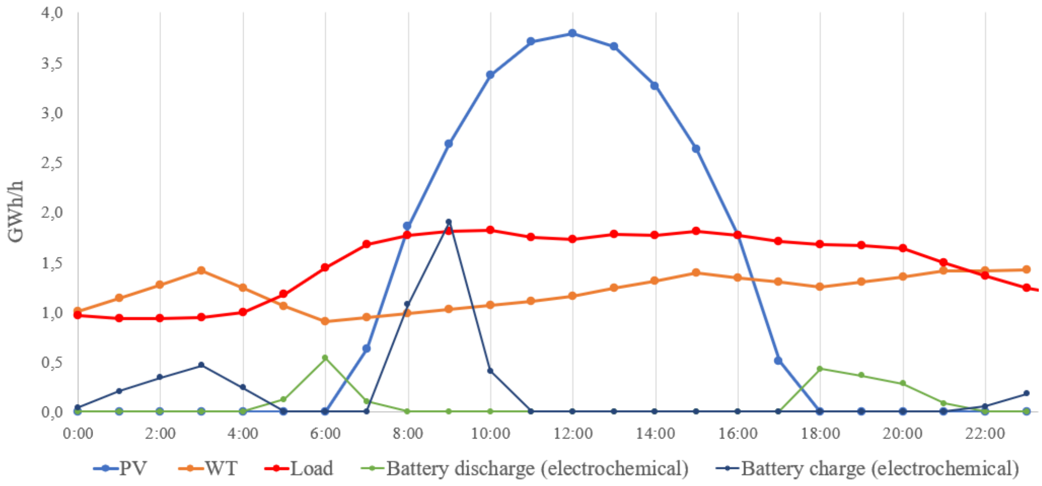

Figure 4. 10 Daily profiles with use of the storage battery for a clear day

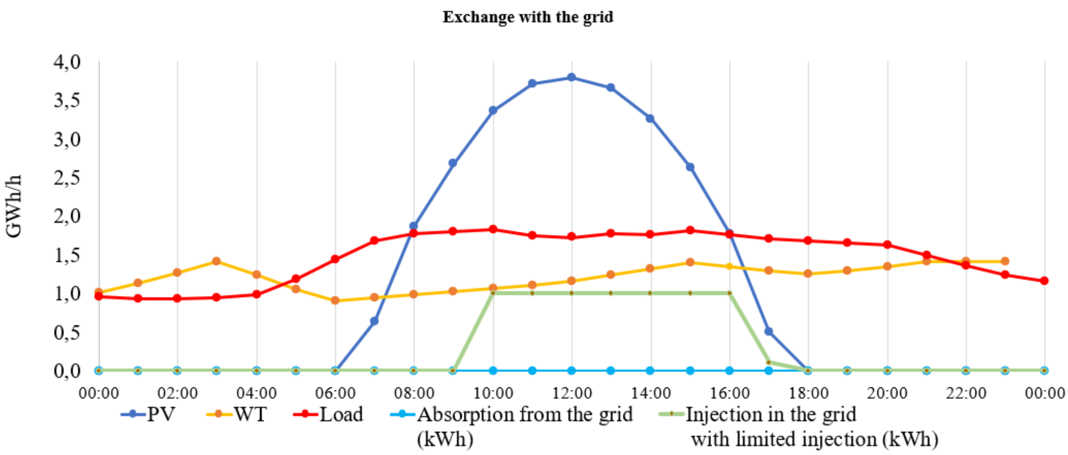

Figure 4. 11 Daily profiles with exchanges with the grid for a clear day

Two other significant days are shown for the analysed site, in particular in *Figure 4.12* is shown a day in which the wind power plant is able to fully satisfy the load. The generation profile of the wind power plant has a constant value equal to the nominal power of the installed system, demonstrating the great availability of the wind resource in the analysed site. This situation occurs mainly in the summer months when the mean wind speed reaches an average of 9 m/s and keeps this value constant for several hours.

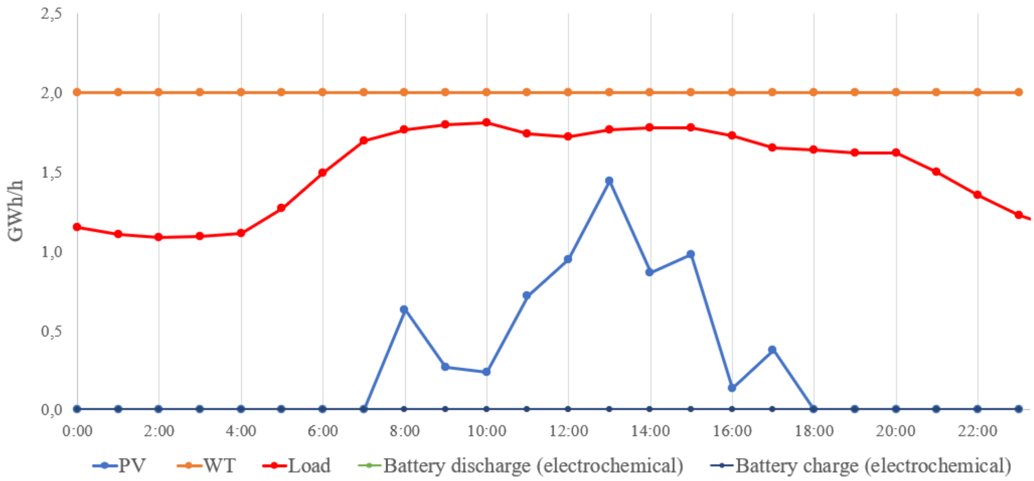

Figure 4. 12 Daily profiles for a day with high availability of wind resource

For site #2 it was analysed how April represents the critical month especially for wind sources. *Figure 4.13* and *4.14* shows a significant day for this month. The generation profile of the wind power plant is significantly lower than the load and the photovoltaic system is active only a few hours per day. For this reason, the storage system is used for several hours as shown in *Figure 4.13*. However, it is not sufficient to completely satisfy the load for all hours of the day, it is therefore necessary to absorb electricity from the external grid as shown in *Figure 4.14*. Energy is mainly withdrawn from the grid at night when wind power production is very low and the PV system is not active.

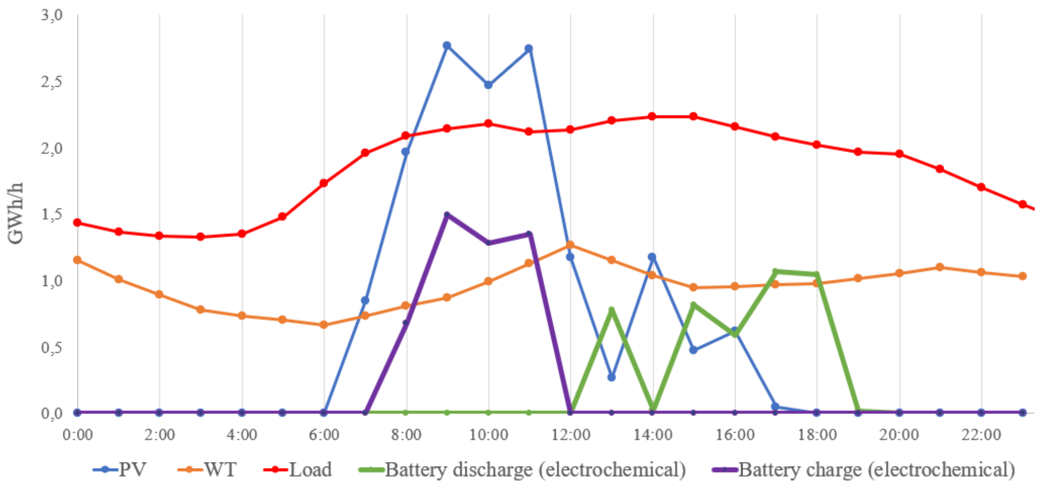

Figure 4. 13 Daily profiles with use of the storage battery, for a day with low availability of the wind resource

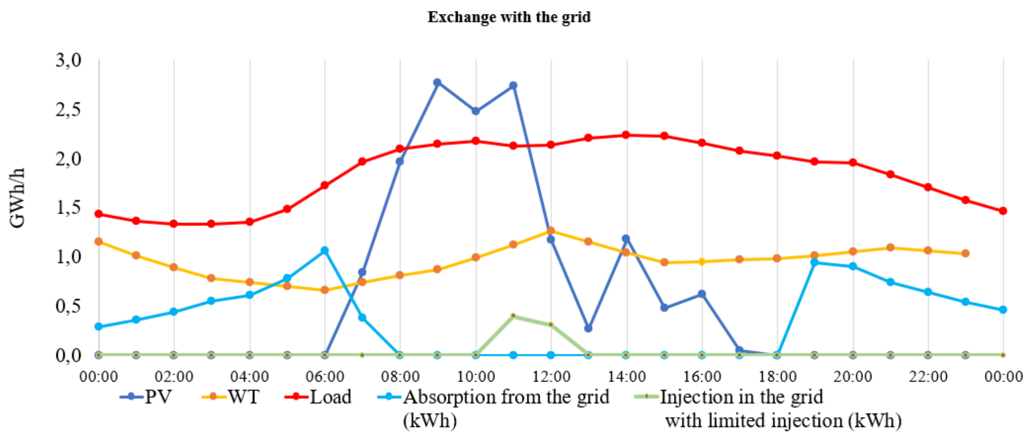

Figure 4. 14 Daily profiles with exchanges with the grid, for a day with low availability of the wind resource

These graphs show how there is a very different situations during the year, in particular: the main difference can be seen with the generation profile of the wind power plant, in which in some days the production is always higher than the load and in others it is much lower. These results are consistent with the wind resource analysis performed previously. The photovoltaic system, on the other hand, has a lower variation. For this reason, it is necessary to provide for the installation of both systems to maximize the level of self-sufficiency.

To calculate self-sufficiency, the "*Risolutore*" function present within the RES_tool program was used. Through this function it is possible to select a parameter that want to maximize, in this case self-sufficiency. The program will be able to find the mathematically optimal solution by returning the optimal values of the variables that can be changed. In this case, the optimization was performed by changing the size of the photovoltaic generator, the wind generator and the storage battery capacity, leaving all other parameters unchanged.

For the maximization of self-sufficiency analysed in this work, several simulations were performed by changing the constraints imposed in order not only to obtain the maximum value of self-sufficiency but in order to respect some physical and economic constraints. Not all the solutions found, even if having a very high self-sufficiency value, were considered acceptable. For this reason, different configurations were analysed and it was evaluated how the system changes according to the different boundary conditions.

In the first simulation performed the constraints imposed are:

- IRR > 12%, this value was higher than the discount rate used in the economic analysis (10%).

- NPV > 0

- $WT_{max,\ size}$ = 8 GW

- $PV_{max,\ size}$ = 1.5 GW

- $E_{storage,max}$ = 1.5 GWh

The maximum value of the power of the generators was imposed to avoid that the program always operate for researches the best solutions, in this way therefore it is possible to avoid the simulations diverging.

Setting a maximum to the value of the IRR also has the advantage of limiting the installation of storage systems, as it could be possible to achieve even 100% self-sufficiency by installing enormous storage capacities, however, given the high costs of these systems. , the project may no longer be profitable.

Table 4.7 shows the results of the first simulations performed. In the first case, the self-sufficiency value reaches 100%; but the systems were oversized, reaching the maximum limit imposed. As can be seen, the production of the generators is much higher than the annual load. It was decided to limit the injection of power fed into the grid to 1 GW and 2 GW respectively as shown in Cases #2 and #3. This limit therefore represents a limit with the exchange of energy with neighbouring countries. However, in this case the generators are still oversized, but having imposed the limit on the input power, high quantities of energy are not produced. Furthermore, the results of this simulations are not acceptable. As an example, in *Figure 4.15* the generation profile for the first week of January referred to Case #2 is shown. As can see, the profile of the wind power plants is much higher than those of the load. In this optimization, the program has provided oversized systems, which do not use more than 60% of the energy they can produce. However, it should be noted that these solutions are mathematically possible and economically advantageous, however they present incompatibilities from a physical point of view.

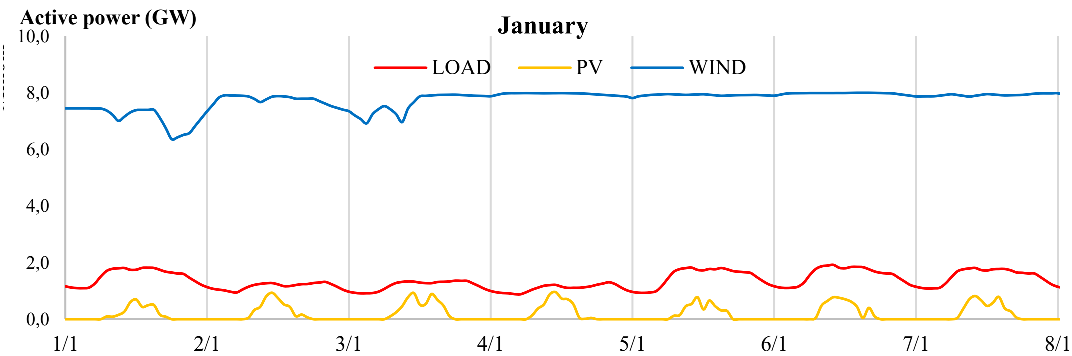

Figure 4. 15 Maximization self-sufficiency, monthly profiles, Case #2

	CASE #1	CASE #2	CASE #3	CASE #4
Limitation of the maximum injection [GW]	-	1.0	2.0	1.0
Size of plants				
Total power of PV generators [GW]	15.0	1.5	1.5	1.5
Productivity of PV [GWh/GW/y]	1288.3	591.1	733.2	856.8
Total power of WT generators [GW]	80.0	8.0	8.0	8.0
Productivity of WT [GWh/GW/y]	6801	2472	3339	2228
Capacity of storage [GWh]	15.0	1.5	1.5	1.5
Energy flows (AC) [FIRST YEAR]				
Production from PV+WT [TWh/years]	563.6	20.7	27.8	19.1
Annual load [TWh/years]	14.1	14.1	14.1	14.1
Injection in the grid [TWh/years]	549.4	7.5	14.6	6.7
Absorption from the grid [TWh/years]	0.1	0.9	0.9	1.7
Grid exchange (abs.+inj.) [TWh/years]	549.5	8.4	15.5	8.4
Battery operation (electrochemical)				
Battery charge [GWh/years]	292.5	65.6	65.6	86.7
Battery discharge [GWh/years]	251.3	57.9	57.9	76.8
Energy balance [FIRST YEAR]				
Self-consumption	2%	64%	47%	65%
Self-sufficiency	**100%**	**93%**	**93%**	**88%**
Absorption from the grid / load	0%	7%	7%	12%
Injection in the grid / load	3885%	53%	103%	47%
Production from renewables / load	3985%	146%	197%	135%
Financial parameters [BASED ON A SINGLE YEAR]				
Initial investment [billion €]	-128.5	-12.9	-12.9	-12.9
NPV after 25 years [billion €]	291.1	4.9	10.3	3.6
IRR	37.1%	15.0%	20.0%	13.7%

Table 4. 7 Results of the simulation on maximization self-sufficiency for Site #2. Part.1

In *Table 4.7* there is also Case #4, this last simulation was performed with the same constraints as Case #2 but refers to year number 4 (2008). The year 2005 taken as a reference for the simulations, has very high mean wind speeds, on the other hand; 2008 is the year with lowest mean wind speeds, as shown previously in *Figure 4.3*. From the results of the simulations, however, it can be seen that the values found are very similar to the simulations performed in the other cases, confirming the low annual variation of the wind resource in the territory in the analysed site.

The following simulations present in *Table 4.8* were performed trying to limit the problems shown above. For this reason, further constraints have been imposed on the simulations, in particular:

- CASE #5: Production to Renewables / Load < 110%

- CASE #6: Production to Renewables / Load < 105%

Through the introduction of this constraint, solutions have been found in which the production of energy is similar to that of the electrical load to be satisfied. In fact, the installed power of the wind power plant is lower than the limit imposed.

- CASE # 7: Not Produced energy < 1%

With the constraint imposed in Case #7, the energy not produced by the plants due to the oversizing of the plants and the limit on feeding into the grid was limited. In this way the size of the photovoltaic and wind power plants was limited. In this case, however, the installation of the storage systems is always at the highest possible levels. The subsequent simulations were carried out by increasing the value of the maximum storage capacity and the size of the PV system, up to 4 GWh and 4 GW respectively. To better analyse this aspect in the further simulations performed, it was decided to increase the maximum value of the IRR which must be respected for economic constraints. As described above, a high IRR value should limit the installation of high storage capacities.

- CASE # 8: Max IRR

- CASE # 9: IRR > 16%

- CASE # 10: IRR > 20%

- CASE # 11: IRR > 30%

The simulation of Case #8 was performed, maximizing the value of the IRR, without any constraint on production, in order to find the maximum admissible value. This corresponds to the minimum value of the capacity of the storage system that can be installed, as shown by the results. In Case #9, the minimum IRR value is set to 16%, this constraint does not impose limit on the installation of the batteries. In the last two cases, however, by increasing the value of the IRR, the capacity of the installable storage decreases, and the maximum value is not reached. These simulations show that when the IRR value varies, the system limits the installation of the storage battery which is very expensive, however decreasing the self-sufficiency value. The simulations carried out in Case #9, #10 and #11 always respect the constraint imposed on the production of energy with respect to the load of less than 105%.

	CASE #5	CASE #6	CASE #7	CASE #8	CASE #9	CASE #10	CASE #11
Limitation of the maximum injection [GW]	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Size of plants							
Total power of PV generators [GW]	1.5	1.5	1.2	0.1	4.0	3.6	2.4
Productivity of PV [GWh/GW/y]	1221	1231	1256	1288	1066	1095	1177
Total power of WT generators [GW]	2.1	1.9	2.0	1.5	1.6	1.7	1.8
Productivity of WT [GWh/GW/y]	6678	6716	6745	6801	6427	6475	6613
Capacity of storage [GWh]	1.5	1.5	4.0	0.1	4.0	3.8	1.0
Energy flows (AC) [FIRST YEAR]							
Production from PV+WT [TWh/years]	15.6	14.8	14.8	10.3	15.6	14.8	14.8

Annual load [TWh/years]	14.1	14.1	14.1	14.1	14.1	14.1	14.1
Injection in the grid [TWh/years]	3.5	2.8	2.8	0.4	3.5	2.8	2.8
Absorption from the grid [TWh/years]	2.1	2.2	2.2	4.2	2.1	2.2	2.2
Grid exchange (abs.+inj.) [TWh/years]	5.5	5.0	5.0	4.6	5.5	5.0	5.0
Battery operation (electrochemical)							
Battery charge [GWh/years]	119.2	149.9	201.8	72.5	765.4	636.5	191.8
Battery discharge [GWh/years]	106.1	133.7	178.4	65.2	685.7	569.9	171.8
Energy balance [FIRST YEAR]							
Self-consumption	78%	81%	81%	96%	84%	84%	81%
Self-sufficiency	85%	85%	85%	70%	88%	88%	86%
Absorption from the grid load	15%	15%	15%	30%	12%	12%	14%
Injection in the grid / load	24%	20%	20%	3%	16%	17%	19%
Production from renewables/load	110%	105%	105%	73%	105%	105%	105%
Financial parameters [BASED ON A SINGLE YEAR]							
Initial investment [billion €]	-4.8	-4.6	-5.6	-2.2	-7.6	-7.2	-5.0
NPV after 25 years [billion €]	8.9	8.6	7.0	7.6	5.0	5.5	8.3
IRR	32.8%	32.6%	26.3%	51.2%	18.6%	20.0%	30.0%

Table 4. 8 Results of the simulation on maximization self-sufficiency for Site #2. Part.2

Subsequently, further simulations, less restrictive from an energy point of view, were carried out. In Case #12, no limit was placed on the storage installation as it was assumed that its size was regulated only by the IRR limit. In Case #13, on the other hand, the limit on the size of the photovoltaic system was also eliminated and it can be seen from the results obtained that the optimal size is slightly higher than the 4 GW limit set in the previous simulations.

- CASE # 12: IRR >16% & Production to Load <105% - No limit to storage

- CASE # 13: IRR >16% & Production to Load <105% - No limit to storage and PV size

The last two simulations were performed by increasing the limit on the production of electrical energy with respect to the electrical load. In particular, the limit was set equal to 120%, in order to take into account the possible increase in the load in the coming years.

- CASE # 14: IRR >16% & Production to Load <120% - No limit to storage

- CASE # 15: IRR > 20% & Production to Load <120% - No limit to storage and PV size

Table 4.9 shows the results obtained for these latest simulations performed, in particular Case #14 will be considered as the base case for subsequent optimization analysis.

	CASE #12	CASE #13	CASE #14	CASE #15
Limitation of the maximum injection	1.0	1.0	1.0	1.0
Size of plants				
Total power of PV generators [GW]	4.0	4.1	4.9	4.1
Productivity of PV [GWh/GW/y]	1071	1062	920	966
Total power of WT generators [GW]	1.6	1.6	2.0	2.1
Productivity of WT [GWh/GW/y]	6427	6413	6105	6189
Capacity of storage [GWh]	5.8	5.6	5.4	3.5
Energy flows (AC) [FIRST YEAR]				
Production from PV+WT [TWh/years]	14.9	14.9	17.0	17.0
Annual load [TWh/years]	14.1	14.1	14.1	14.1
Injection in the grid [TWh/years]	2.2	2.2	4.1	4.3
Absorption from the grid [TWh/years]	1.6	1.6	1.3	1.5
Grid exchange (abs.+inj.) [TWh/years]	3.8	3.8	5.4	5.7
Battery operation (electrochemical)				
Battery charge [GWh/years]	933.2	959.6	564.8	372.9
Battery discharge [GWh/years]	838.1	862.1	506.5	335.3
Energy balance [FIRST YEAR]				
Self-consumption	84%	84%	76%	75%
Self-sufficiency	89%	89%	91%	90%
Absorption from the grid / load	11%	11%	9%	10%
Injection in the grid / load	16%	16%	29%	30%
Production from renewables / load	105%	105%	120%	120%
Financial parameters [BASED ON A SINGLE YEAR]				
Initial investment [billion €]	-8.4	-8.5	-9.6	-8.1
NPV after 25 years [billion €]	3.7	3.7	4.3	6.2
IRR	16%	16%	16%	20%

Table 4. 9 Results of the simulation on maximization self-sufficiency for site #2. Part.3

The obtained values of self-sufficiency are very high, in all the simulations performed. This result was confirmed by the analysis on the simultaneity of resources performed in *Paragraph 4.1*, in which the presence of wind or solar resources for the analysed site reached 98% of the total number of hours. A high availability of the wind resource during the night hours allows to better satisfy the load and reducing the absorption from the grid.

The graphs shown above (*Figure 4.10-.11-.12-.13-.14*) with the daily profile, were obtained from the simulations of Case #14.

The graph in *Figure 4.16* show the monthly trends for first week of April. In this graph, absorption from the grid indicates the need to purchase energy from neighbouring countries and the injection indicates the sale of excess energy. In this month, the production of energy by the wind system was lower than in the other months and consequently more exchanges with the grid occur. The graph shows how the absorption from the grid occurs every day and mainly takes on the maximum value when the load is higher. The excess energy produced is fed into the grid, however this value was limited by the maximum power limit equal to 1 GW, as can be seen from the graph, in fact; the injection is present every day and concentrated mainly in the daily hours, in which the solar system production is maximum. The value of production from wind farms, on the other hand, has a very constant value throughout the month, and is therefore suitable for satisfying the load even at night. The generation production curve presents peaks in correspondence with the use of the photovoltaic system.

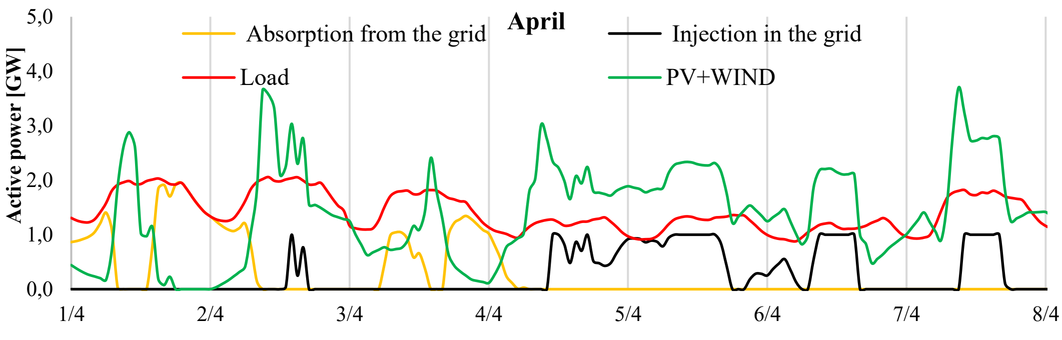

Figure 4. 16 Maximization of self-sufficiency, monthly profiles with absorption and injection in the grid

Figure 4.17 shows the annual production level for both photovoltaic and wind systems. In the planning phase, systems with different characteristics can be installed to increase the level of self-sufficiency. In fact, as can be analysed in the graph, the production by the wind power plant is very high in the summer months, but in the winter months and especially in April it drastically reduces. For this reason, the program also considers, in its optimal configuration, an important quantity of photovoltaic system, capable of supporting the wind system. In this way, was guaranteed a high level of energy self-sufficiency in the months of low productivity. In fact, the solar source has a much lower variation than the wind one, in fact, again from the graph in *Figure 4.17* it can be seen how the productivity between the various months is almost constant. Furthermore, the only data to be analysed is not only linked to productivity but also the variation of the source must be analysed. Furthermore, in addition to the seasonal variation that can occur during the various months of the year, it is also necessary to consider the variation between the different years, which is not shown in the graph. The main problem of renewable sources was linked to this difficulty in forecasting resources and their uncertainty; therefore, considering different systems with different sources could reduce these issues. The annual values of self-sufficiency, and the exchange with other countries was also reported in *Figure 4.18*. The value of self-sufficiency energy has very high values throughout the year. The month in which the minimum value is April, and consequently has the maximum absorption from the external countries. In the summer months, the absorption reaches the low limit values, increasing the value of self-sufficiency.

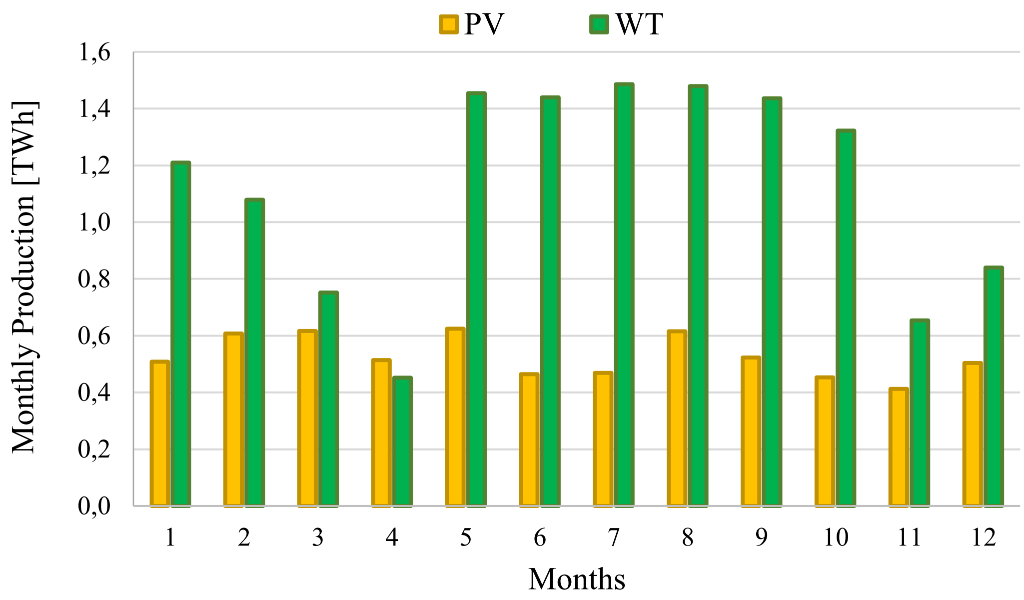

Figure 4. 17 Maximization of self-sufficiency, monthly production of the photovoltaic and wind power plant

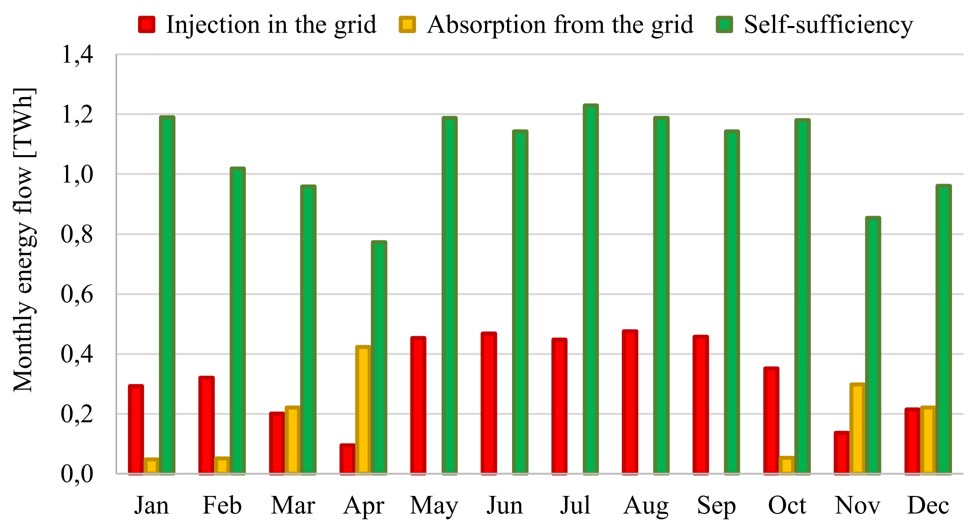

Figure 4. 18 Maximization of self-sufficiency, annual exchanges with the grid and monthly value of self-sufficiency energy

From the results of the *Table 4.9*, this configuration found allows to maximize self-sufficiency, reaching 91%, but also allows to have an excellent economic return on investment. In fact, the NPV value calculated after 25 years is positive and the IRR is 16%. For the calculation of the NPV, the positive cash flows are those due to self-consumed energy and therefore not purchased from the external grid and from the sale of electricity to other country. In this case, the self-consumed energy was valued at 0.11 $/kWh and the selling price was instead equal to 0.09 $/kWh, both for PV systems and for wind systems. The negative cash flows are instead due to the initial investment cost and annual maintenance costs. *Figure 4.19* shows the calculation of the NPV, every 10 years there is a replacement of the battery, for this reason the curve is not always increasing and in the year 10 and 20 there are negative cash flows. The payback time (PBT) occurs after about 9 years.

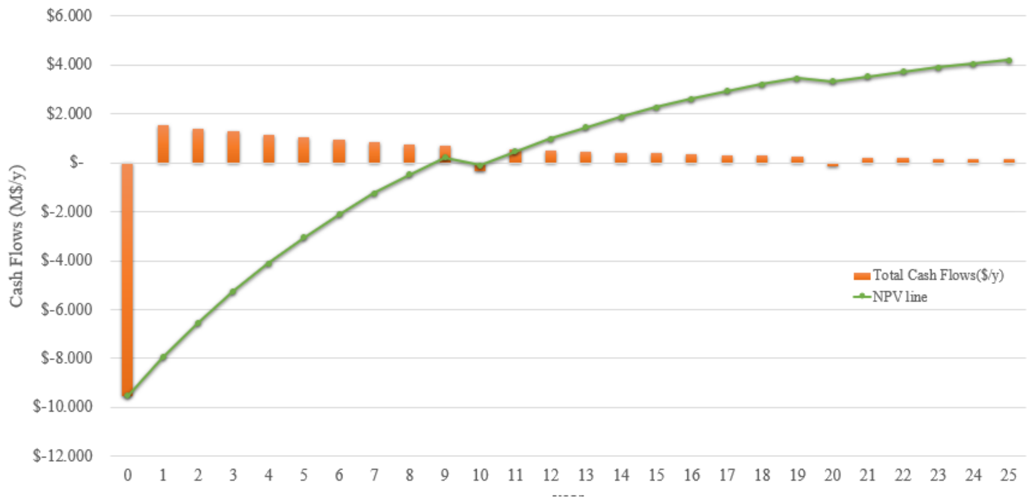

Figure 4. 19 Maximization of self-sufficiency, NPV trend for Site #2

Furthermore, from the production data it is possible to calculate the LCOE value of the plants, in particular for PV systems the LCOE is equal to 0.11 $/kWh and for wind 0.03 $/kWh.

4.4 Energy Sensitivity Analysis

In the previous paragraph, different configurations were evaluated for site #2, imposing some constraints and looking for a solution that is both physically and economically suitable. In this section was analysed different scenarios based on the 25-year dataset. Within the RES_tool program it is possible to perform sensitivity analysis on 10 different cases, for a period of 25 years. Through the sensitivity analysis it is possible to analyse how the fundamental parameters varied, when some input data change and to analyse different scenarios. The sensitivity analysis can be performed both at an energy and financial level, in this paragraph was considered the energy part.

From the preliminary analysis carried out, it was analysed how an optimal configuration provides for the installation of about 2 GW of wind power plants and 4.9 GW of photovoltaic systems. With these data, the wind farms are able to satisfy most of the load, given the high productivity of the site analysed (site #2). For the sensitivity analysis also performed for the same site, production by renewable generators was considered to be 120% of the annual Sri Lankan load. Through the productivity of the single generator systems used, it is possible to perform simulations by imposing the production percentage for each plant. Different sizes were also evaluated for the storage system in order to analyse the optimal configuration. In this case, from the data obtained above, the optimal storage size obtained was 5.4 GWh, in this case, three different configurations were analysed (low, medium and high level). Before carrying out the sensitivity analysis, it was noted, from the previously optimized configuration, that a storage system with a capacity greater than 7 GWh was not able to satisfy the economic constraints imposed, in particular the IRR value is lower the discount rate imposed and the NPV is negative after 25 years. This data was therefore used as an upper limit for subsequent analysis. For the energy sensitivity, the size of the generators and the storage system was varied, and it was analysed in particular how the value of self-sufficiency and some financial parameters change. Financial data has not been changed and is the same of previous simulations.

The input data of the first simulation are shown in *Table 4.10*.

	50% PV - 50% WT			**70% PV - 30% WT**			**30% PV - 70% WT**			**10% PV 90% WT**
	CASE #1	CASE #2	CASE #3	CASE #4	CASE #5	CASE #6	CASE #7	CASE #8	CASE #9	CASE #10
PV [GW]	8.5	8.5	8.5	11.9	11.9	11.9	5.1	5.1	5.1	1.7
WT [GW]	1.4	1.4	1.4	0.8	0.8	0.8	1.9	1.9	1.9	2.5
Storage [GWh]	2	5	6.5	2	5	6.5	2	5	6.5	6.5

Table 4. 10 Different size configurations of the system for the input of the sensitivity analysis. Part.1

Given the high productivity of the wind power plant for site #2, in Case #10 a configuration was evaluated in which the energy production was strongly satisfied by the wind generators.

Figures 4.20 and *4.21* show the main results of the simulations performed

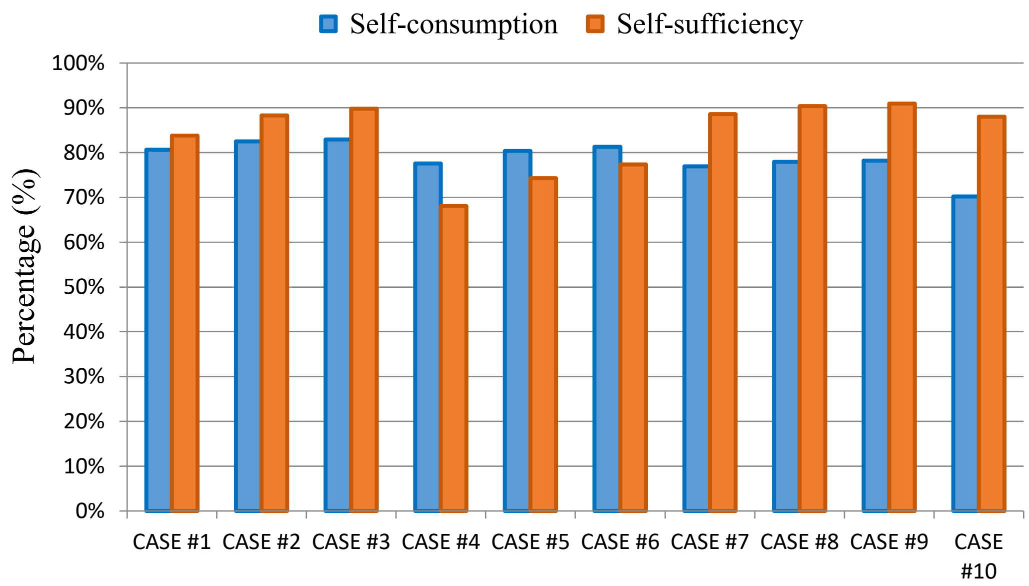

Figure 4. 20 Self-sufficiency value for 10 simulation cases. Part.1

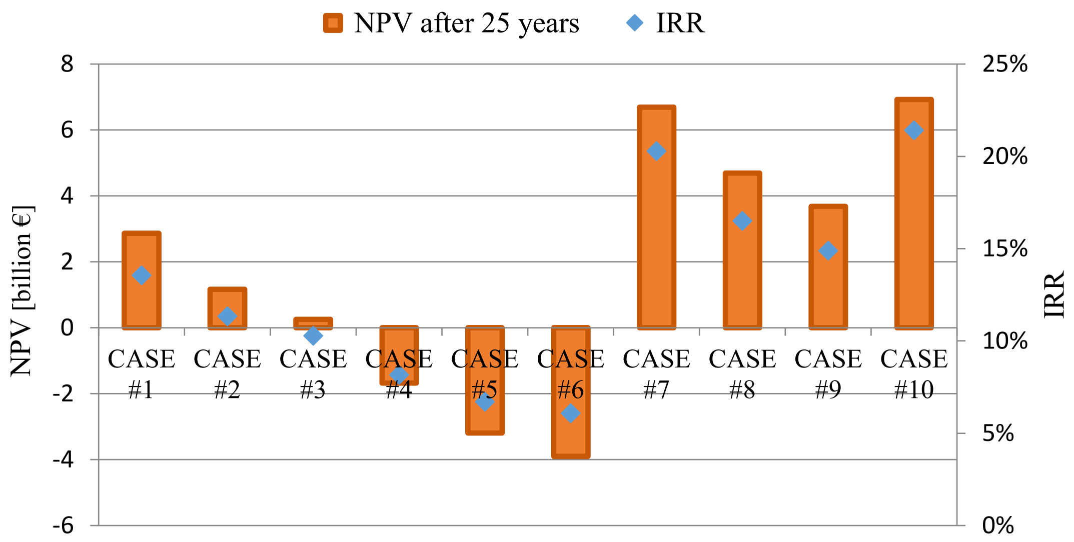

Figure 4. 21 Economic output parameters for 10 simulation cases. Part.1

It is immediately evident how the value of self-sufficiency is very high in all the cases analysed, however from the graph in *Figure 4.21*, the NPV value after 25 years is negative for Cases #4, #5 and #6, i.e. in those cases in which the energy production is mainly satisfied by the photovoltaic system. The NPV and IRR value decreases in cases where the storage system has a greater capacity, consequently the value of self-sufficiency tends to grow. Also note the latest cases shown, in particular from cases #7 to #9, the self-sufficiency value reaches almost 90%, and when the size of the storage varies, there are no particular differences in the level of self-sufficiency. In this case, in fact, the size of the wind system is similar to the optimized configuration found previously, equal to 2 GW. From an economic point of view, however, there are several differences between the cases analysed, in fact case #7 has a much higher NPV value than subsequent cases due to the limited installed capacity.

Subsequently, further simulations were carried out by varying the percentage of generation and the size of the storage. The input data is shown in the *Table 4.11*.

	60% PV - 40% WT						40% PV - 60% WT			100% WT
	CASE #11	CASE #12	CASE #13	CASE #14	CASE #15	CASE #16	CASE #17	CASE #18	CASE #19	CASE #20
PV [GW]	10.2	10.2	10.2	10.2	10.2	10.2	6.8	6.8	6.8	-
WT [GW]	1.1	1.1	1.1	1.1	1.1	1.1	1.6	1.6	1.6	2.7
Storage [GWh]	0.5	1	1.5	2	2.3	2.5	2	5	6.5	6.5

Table 4. 11 Different size configurations of the system for the input of the sensitivity analysis. Part.2

In cases #4, #5 and #6, as the storage size decreased, the economic constraints were not satisfied and even in the configuration in which the storage was not present in the plant configuration. In cases #11, #12, #13, #14, #15 and #16 was analysed the system in which the production is mostly generated by the photovoltaic system and with a lower storage capacity than in the previous cases. From the results shown in *Figure 4.22* it can be seen that in case #16, the NPV is near to zero and the IRR value is equal to the value of the discount rate set. Further simulations conducted with this configuration, increasing the size of the storage system would have created economically not advantageous configurations. Also note the case #20 was analysed the configuration in which all the electrical load was satisfied by the wind power generation system. In this case, the system is economically very advantageous, and also the value of self-sufficiency achieved is very high, above 80%, as shown in *Figure 4.23*.

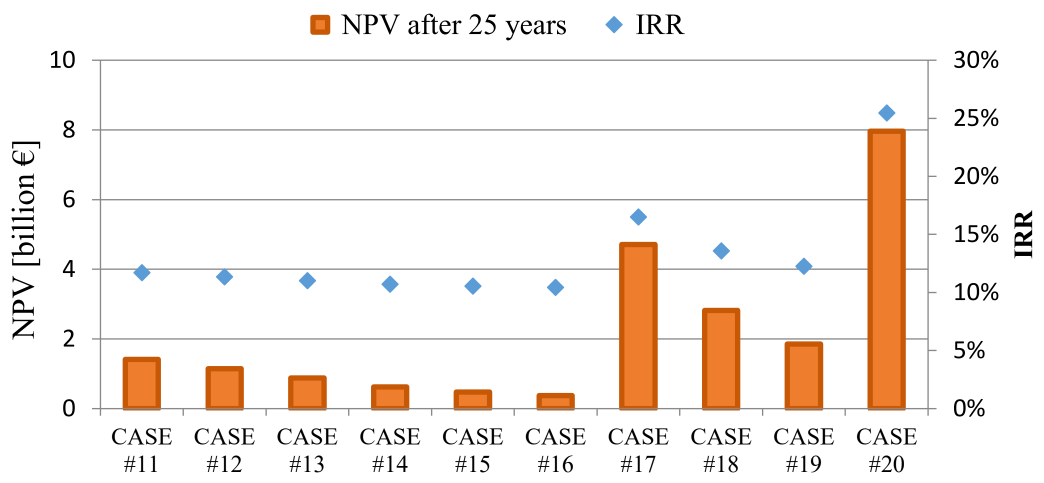

Figure 4. 22 Self-sufficient for 10 simulation cases. Part.2

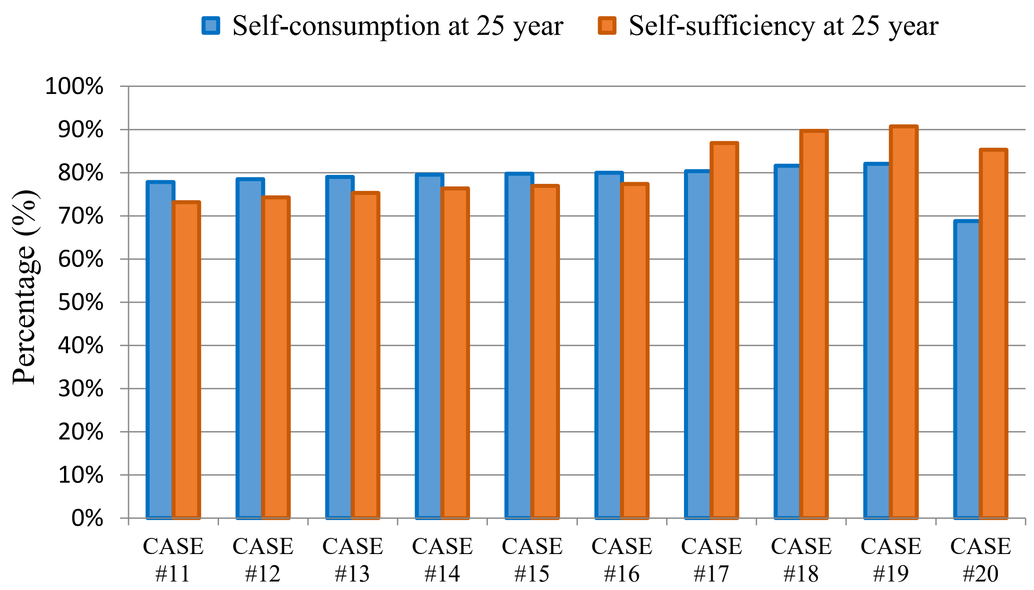

Figure 4. 23 Economic output parameters for 10 simulation cases. Part.2

From the results of the 20 simulations performed, the level of self-sufficiency achieved is always higher than 70% and in some configurations it has even reached 90%. These values were achieved thanks to the high productivity of the wind resource for the analysed site. The site is very suitable to the installation of wind farms.

Please note that the simulations performed refer to the entire load of Sri Lanka, the exchanges with the grid therefore represent the exchanges of energy with neighbouring foreign countries. In the simulations carried out with the sensitivity analysis, no restrictions were placed on the injection of electricity into the grid. *Figures 4.24* and *4.25* show the exchanges with the grid for the various cases analysed. As is evident, the cases with a low installed storage capacity have a high annual absorption. Furthermore, the greatest absorption occurs in cases where the production of electricity is mainly produced by photovoltaic systems. The solutions with the lower absorption are when production was generated more to wind farms and with high storage capacity. However, analysing the data on the injection of electricity into the grid, it can be seen that cases #10 and #20, i.e. in which the production is mainly and exclusively by wind system, the injection into the grid has a very high value, higher than 5 TWh. This value is very high when compared with Sri Lanka's annual electricity consumption which is 14.9 TWh in 2019 [19]. With these configurations, therefore, about 35% of the national consumption was exchanged with foreign countries. The cases with a more heterogeneous distribution allow to reach lower values.

In the analysis of the country's energy self-sufficiency and in the import and export balance, carried out so far, the hydroelectric source, has not been considered. In Sri Lanka the installed capacity of this source in 2020 is 1.8 GW [18] with an annual production of 4.8 TWh [19]. The quantity of energy absorbed by the grid and therefore coming from external countries could be satisfied by this additional source, increasing the level of self-sufficiency of the country produced mainly from renewable sources.

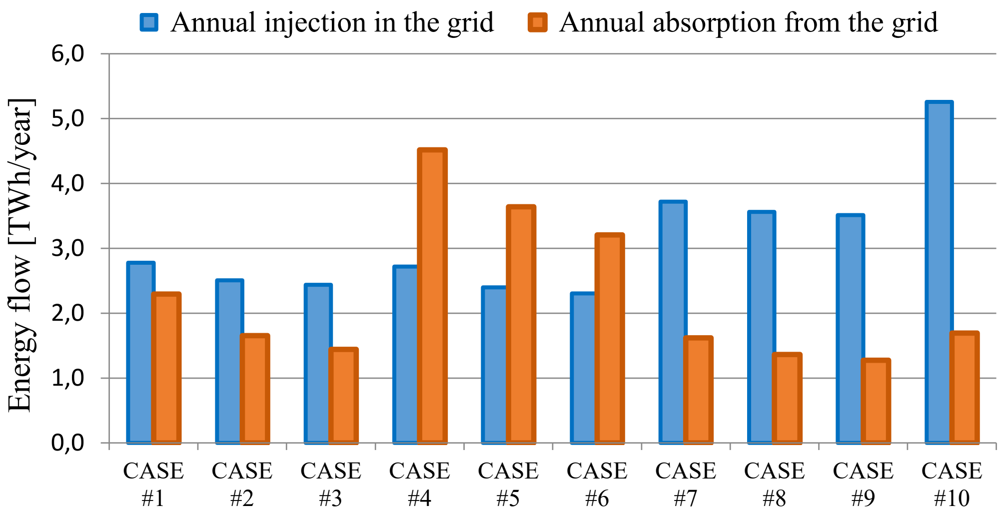

Figure 4. 24 Exchanges with the grid for 10 simulations. Part. 1

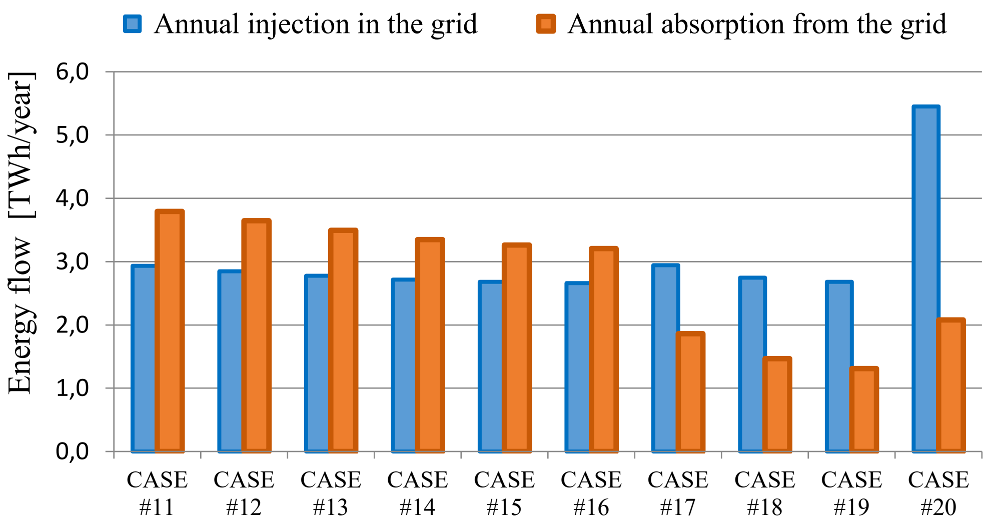

Figure 4. 25 Exchanges with the grid for 10 simulations. Part. 2

4.4.1 Local Energy Sensitivity Analysis

Subsequently, the sensitivity analysis was applied to other sites with different distribution resources. 4 different locations were selected, from the analysis of *Chapter 2*: sites #3, #4, #7 and #10. Through this process is possible to found the optimal configuration of the size of the systems to meet the load of the region of the installation sites.

To perform this analysis, the total Sri Lankan load was adapted to the region, to realize the local load, therefore, the population data was used to proportion the national load. The same method described in the previous paragraph was used for the size of the generators, i.e. the maximum production equal to 120% of the load was calculated and the generators were sized with the data on the productivity of the selected location. In this work, was decided to analyse large plants capable of satisfying a load of different type of users.

Site #10 - Vadamarachchi

Site #10 has a very similar resources distribution of site #2, with a high productivity of the wind resource, about 6600 MWh/MW/y. The annual variability of the wind energy production is 8.4% and the solar one 2.1%. These data are consistent with the analysis performed in *Chapter 2*, in fact this site was selected for the installation of wind farms. The input data of the sensitivity analysis performed are shown in *Table 4.12*.

Site #10	**50% PV - 50% WT**			**60% PV - 40% WT**			**40% PV - 60% WT**			**10% PV 90% WT**
	CASE #1	CASE #2	CASE #3	CASE #4	CASE #5	CASE #6	CASE #7	CASE #8	CASE #9	CASE #10
PV [MW]	280	280	280	330	330	330	220	220	220	50
WT [MW]	70	70	70	50	50	50	80	80	80	120
Storage [MWh]	100	250	400	26	78	130	100	250	400	400

Table 4. 12 Different size configurations for the input of the sensitivity analysis, Site #10

In this case the results are similar to those obtained for site #2, in fact the level of self-sufficiency has very high values, especially in the configuration with greater use of the wind source. In the simulations in which the production from photovoltaic systems is greater, to respect the economic constraints; it is necessary to reduce the size of the storage systems. The maximum value of self-sufficiency was reached in case #9, even exceeding 90%, as shown by *Table 4.13*, which also summarizes the main results calculated.

Site #10	CASE #1	CASE #2	CASE #3	CASE #4	CASE #5	CASE #6	CASE #7	CASE #8	CASE #9	CASE #10
NPV [M€]	435.7	334.0	230.5	412.2	377.5	342.6	456.2	353.1	248.8	335.3
IRR [%]	23.6	19.3	15.9	23.2	21.6	20.1	25.8	20.8	16.9	21.4
Self-sufficiency	82%	87%	90%	69%	71%	73%	86%	89%	91%	88%

Table 4. 13 Output parameters of sensitivity analysis, Site #10

Site #7 – Puttalam

Site #7 was also selected for the installation of wind farms. However, this site has a lower productivity than the two sites analysed previously (2500 GWh/GW/y) and an annual variability of the wind source of about 38%, while the solar one is 2.6%.

In this case, a simulation was also performed in which only the presence of the wind generators was considered, without the photovoltaic systems.

Site #7	**50% PV - 50% WT**			**60% PV - 40% WT**			**40% PV - 60% WT**			**100% WT**
	CASE #1	CASE #2	CASE #3	CASE #4	CASE #5	CASE #6	CASE #7	CASE #8	CASE #9	CASE #10
PV [MW]	550	550	550	700	700	700	470	470	470	-
WT [MW]	400	400	400	320	320	320	480	480	480	800
Storage [MWh]	230	590	760	230	590	760	230	590	760	760

Table 4. 14 Different system size configurations for the sensitivity analysis input, Site #7

The highest values of self-sufficiency were reached in cases #3 #6 and #9 or where the storage capacity is maximum. Case #10 has the lowest value of self-sufficiency and also the economic return on investment is very low, demonstrating the low productivity of the site compared to the previous ones.

Site #7	CASE #1	CASE #2	CASE #3	CASE #4	CASE #5	CASE #6	CASE #7	CASE #8	CASE #9	CASE #10
NPV [M€]	506.2	243.9	115.1	519.4	255.4	125.9	521.0	260.0	134.1	96.6
IRR [%]	15.6	12.5	11.2	15.6	12.6	11.2	15.6	12.6	11.3	10.9
Self-sufficiency	66%	71%	73%	65%	70%	72%	67%	71%	73%	58%

Table 4. 15 Output parameters of sensitivity analysis, Site #7

Site #5 - Mutur

The subsequent sites analysed, #3 and #5 were selected for the installation of photovoltaic generators. However, site #5 has a good availability of wind resources with a variability of 10% and a productivity of 5200 GWh/GW/y. The variability of the solar source is 1.5%.

Site #5	**50% PV - 50% WT**			**60% PV - 40% WT**			**40% PV - 60% WT**			**10% PV 90%WT**
	CASE #1	CASE #2	CASE #3	CASE #4	CASE #5	CASE #6	CASE #7	CASE #8	CASE #9	CASE #10
PV [MW]	410	410	410	490	490	490	330	330	330	80
WT [MW]	130	130	130	100	100	100	150	150	150	230
Storage [MWh]	155	385	500	40	116	193	155	385	500	500

Table 4. 16 Different system size configurations for the sensitivity analysis input, Site #5

In this case, high values of self-sufficiency were achieved, in particular in case #3 and case #9. But the maximum return on investment achieved by installing more photovoltaic system (Case #4).

Site #5	CASE #1	CASE #2	CASE #3	CASE #4	CASE #5	CASE #6	CASE #7	CASE #8	CASE #9	CASE #10
NPV [M€]	565.5	393.0	323.1	572.2	521.0	471.5	596.2	423.1	353.2	474.9
IRR [%]	21.4	17.1	15.6	21.7	20.3	18.9	22.9	18.1	16.5	20.2
Self-sufficiency	79%	83%	85%	70%	72%	74%	81%	84%	85%	80%

Table 4. 17 Output parameters of sensitivity analysis, Site #5

Site #3 - Badulla

In the last case analysed, the distribution of resources is very different from the other sites. The variability of the wind source is 84%. The mean wind speeds ranging between 3.5 m/s in 2005 and 1.3 m/s in 2014. For this reason, this site therefore does not suitable for the installation of wind farms. The solar resource, on the other hand, has more favourable conditions with a productivity of 1400 GWh/GW/y and an annual variability of 2.9%.

Site #3	**50% PV - 50% WT**			**60% PV - 40% WT**			**40% PV - 60% WT**			**100% PV**
	CASE #1	CASE #2	CASE #3	CASE #4	CASE #5	CASE #6	CASE #7	CASE #8	CASE #9	CASE #10
PV [MW]	240	240	240	290	290	290	190	190	190	500
WT [MW]	120	120	120	100	100	100	150	150	150	-
Storage [MWh]	80	200	260	80	200	260	80	200	260	150

Table 4. 18 Different system size configurations for the sensitivity analysis input, Site #3

In this case it was possible to perform a simulation (Case #10) in which the installation of a photovoltaic system was performed without the need to also install a wind power plant. In the latter case, it was necessary to reduce the size of the storage to satisfy economic constraints. In fact, the results in *Table 4.19* show how the value of the IRR is very low in this last case and similar to the value of the discount rate in the economic analysis. The value of self-sufficiency achieved in Case #10 does not reach 50%. Furthermore, in this site there is no clear different between the various simulated cases, precisely because the wind source is not clearly superior to the solar one.

Site #3	CASE #1	CASE #2	CASE #3	CASE #4	CASE #5	CASE #6	CASE #7	CASE #8	CASE #9	CASE #10
NPV [M€]	170.9	86.2	42.9	165.4	80.4	37.2	184.2	99.7	56.5	43.0
IRR [%]	15.2	12.5	11.2	14.9	12.2	11.0	15.7	12.9	11.6	11.1
Self-sufficiency	69%	74%	76%	67%	72%	74%	71%	75%	77%	48%

Table 4. 19 Output parameters of sensitivity analysis, Site #3

4.5 Maximization of the economic return

A further goal to be achieved is to maximize the economic return on investment. To perform this analysis, it is possible to take into account both the NPV value calculated after 25 years and the IRR. As in the case of maximizing self-sufficiency, the "*Risolutore*" function of the RES_tool program was also used in this analysis. The case analysed is always the site #2 with the electrical load of the entire country. The exchanges with the grid also represent the exchanges of electricity with foreign countries

The configurations analysed are shown in the *Table 4.20:*

	Cases	Descriptions
MAX NPV	Case #1	No limitations
	Case #2	Limit to injection = 1 GW
	Case #3	- Limit to injection = 1 GW - Production/Load < 120%
MAX IRR	Case #4	Limit to injection = 1 GW
	Case #5	- Limit to injection = 1 GW - Production/Load > 80%
	Case #6	- Limit to injection = 1 GW - Production/Load > 100%
	Case #7	- Limit to injection = 1 GW - Production/Load > 120%

Table 4. 20 Maximization of economic return, input data and constraints

Firstly, the optimization was performed by maximizing the NPV value, placing only constraints on the maximum size of the plant. The constraints imposed are equal to 10 GW for the size of the photovoltaic system and 20 GW for the wind system. From the solutions shown in Case #1 of *Table 4.21* it can be seen how these constraints were achieved and the production of electrical energy is 1053% respect to the electric load. The system was oversized, however the presence of the storage battery was not provided. In the subsequent simulations, was imposed the constraint of 1 GW for the exchange of electricity with foreign countries as in the case of maximizing self-sufficiency. In Case #2, by maximizing NPV, the program solutions oversize the system, in fact the production with respect to the load is equal to 128%. In Case #3, the constraint was set to keep this last parameter below 120%.

Simulations #4, #5, #6 and #7 were performed trying to maximize the IRR value. In Case #4, the results obtained show how the system was undersized, with a production compared to the load of 54%. In Case #5, the limit was set to obtain a production value of at least 80% of the load. In Case #6 the constraint was raised to 100% and in Case #7 to 120%. With an oversized system, more energy was produced than necessary, therefore the value of self-sufficiency is very high, because most of the load will be satisfied by the energy produced by local generators as in Case #2. In undersized systems, as in Case #4, most of the energy produced was used to meet the load and exchanges with the grid were limited. In this case, therefore, the value of self-consumption is very high. From the results of *Table 4.21* it is possible to observe this situation, in fact in Case #4 the value of self-consumption is equal to 100%.

By imposing the constraint on production, the results obtained for maximizing NPV (Case #3) are the same as those obtained with maximizing IRR (Case #7), as shown in *Table 4.21*.

	CASE #1	CASE #2	CASE #3	CASE #4	CASE #5	CASE #6	CASE #7
Limitation of the max. injection [GW]	-	1	1	1	1	1	1
Size of plants							
Total power of PV generators [GW]	10.0	-	-	-	-	-	-
Productivity of PV [GWh/GW/y]	1289	-	-	-	-	-	-
Total power of WT generators [GW]	20.0	2.9	2.6	1.1	1.7	2.1	2.6
Productivity of WT [GWh/GW/y]	6801	6194	6590	6801	6801	6799	6592
Capacity of storage [GWh]	-	-	-	-	-	-	-
Energy flows (AC) [FIRST YEAR]							
Production from PV+WT [TWh/years]	148.9	18.2	17.0	7.6	11.3	14.1	17.0
Annual load [TWh/years]	14.1	14.1	14.1	14.1	14.1	14.1	14.1
Injection in the grid [TWh/years]	135.3	6.2	5.1	0.01	0.8	2.7	5.1
Absorption from the grid [TWh/years]	0.5	2.1	2.3	6.55	3.6	2.7	2.3
Grid exchange (abs.+inj.) [TWh/years]	135.8	8.3	7.5	6.56	4.4	5.3	7.4
Energy balance [FIRST YEAR]							
Self-consumption	9%	66%	70%	100%	93%	81%	70%
Self-sufficiency	97%	85%	84%	54%	74%	81%	84%
Absorption from the grid / load	3%	15%	16%	46%	26%	19%	16%
Injection in the grid / load	957%	44%	36%	0%	5%	19%	36%
Production from renewables/load	1053%	128%	120%	54%	80%	100%	120%
Financial parameters [BASED ON A SINGLE YEAR]							
Initial investment [billion €]	-35.9	-4.0	-3.5	-1.52	-2.3	-2.8	-3.5
NPV after 25 years [billion €]	77.9	12.1	11.7	5.8	8.4	10.1	11.7
IRR	36%	46%	49%	54%	54%	52%	49%

Table 4. 21 Maximization of economic return, main simulation results

From the results obtained, it can be seen that the value of self-sufficiency achieved in some cases is very high, even higher than 80%. This result was justified by the fact that the profitability of the plant derives from the economic savings that were generated when the load was satisfied by a local generators and not by purchasing electricity from the grid. Note that in the cases analysed, the storage system is not present. This result highlights how it is economically more advantageous to purchase electricity from the external grid rather than install a very expensive electrochemical storage system.

Analysing Case #2, with no restrictions imposed on production, the value of the NPV after 25 years is 12.1 billion €, or more than 300% of the initial investment.

A further consideration that can be carried out from the results of *Table 4.21*: the program does not provide the presence of the photovoltaic system. The production is then completely satisfied to the wind power plant, which for the analysed site has a very high productivity. The results are therefore consistent with those obtained on maximization of self-sufficiency and with the energy sensitivity analysis, in which the solutions with the highest NPV were achieved when in the plant configuration the production was mostly satisfied to the wind power plant.

As noted previously, in cases where the objective function is the maximization of the NPV, the system was oversized with respect to the load, the opposite is the situation in which the IRR is to be maximized. The NPV was expressed in absolute value and in this case it was represented in billions of euros; the IRR, on the other hand, is a percentage value and does not depend on the size of the plant. Both indicators are useful for evaluating the profitability of a project, however the NPV provides information on the economic surplus that can be had on a project by evaluating all annual cash flows. The IRR, on the other hand, provides information on the "non-profit point", so when the positive cash flows equal the negative ones. *Figure 4.26* and *Figure 4.27* show the trend of the NPV and cash flows in Case #2 and in Case #4. If was maximized the NPV, the value obtained after 25 years is higher than that of Case #4, respectively equal to 12.1 and 5.8 billion €. However, the PBT (*Pay Back Time*), was reached earlier in the event that the IRR was maximized.

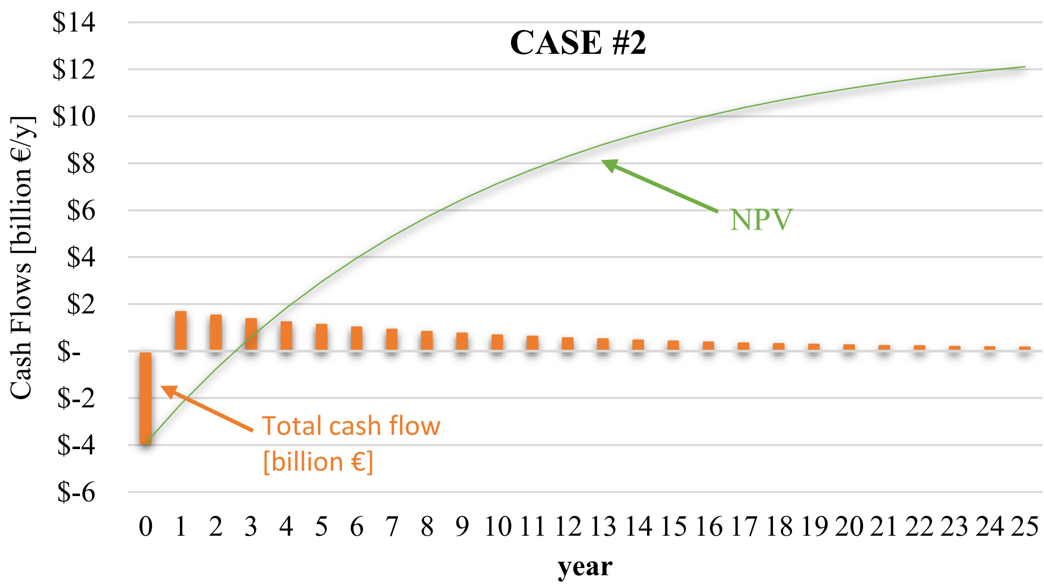

Figure 4. 26 Maximization of economic return, NPV trend for Case #2

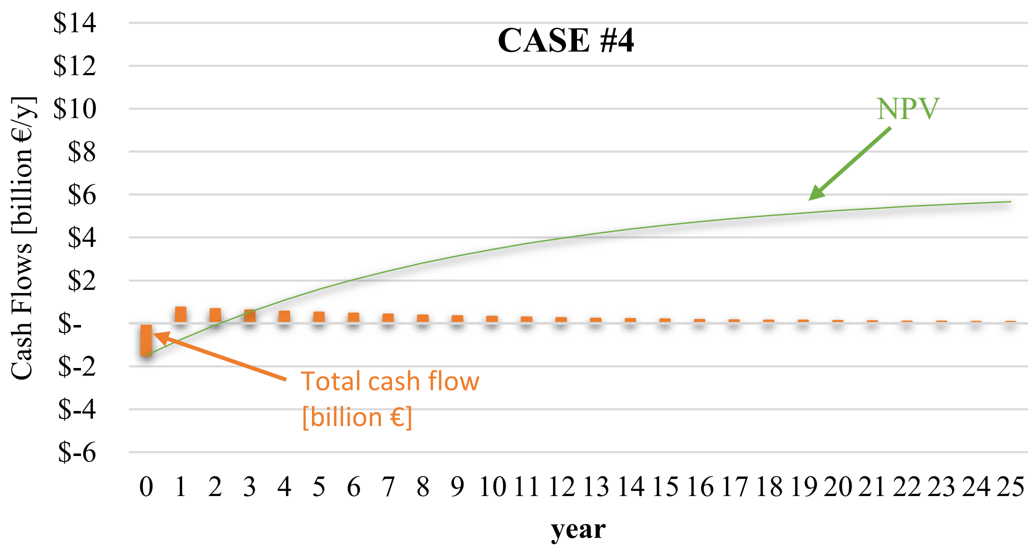

Figure 4. 27 Maximization of economic return, NPV trend for Case #4

Considering Case #4 where the system was undersized with a production of 54% compared to the electric load. It is possible to compare this case with the results obtained for the maximization self-sufficiency. In particular, in the configuration of Case #4 neither the photovoltaic system nor the storage system was considered to meet the load. So, was required an higher absorption from the grid. From *Figure*

4.28 it can also be seen that in this case the injection of electricity into the grid never occurs. In the case of maximizing self-sufficiency (*Paragraph 4.3*), the absorption from the grid was limited by the presence of the electrochemical storage system, and the absorption occurs above all in cases where the production by the wind system was low. In the case of an undersized system, however, the absorption has very high values in every month, even in the summer months when the producibility of the system is very high. It is therefore concluded that for the selected site, the presence of an adequately sized storage system allows to greatly limit the absorption from the electricity grid and in a few months reducing this value to zero. Without an storage system and with an undersized plant, the economic return on investment is very high and the PBT was reached very soon, after about 2 years. However the selected site is very dependent on absorption of electricity from the neighbouring countries. If, on the other hand, was evaluated the case in which NPV was maximized, the results obtained are very similar to those obtained on maximizing self-sufficiency (*Figure 4.29)*. In fact, even in this case the absorption from the grid is zero in the summer months, and the injection into the grid reaches very high values in the summer months.

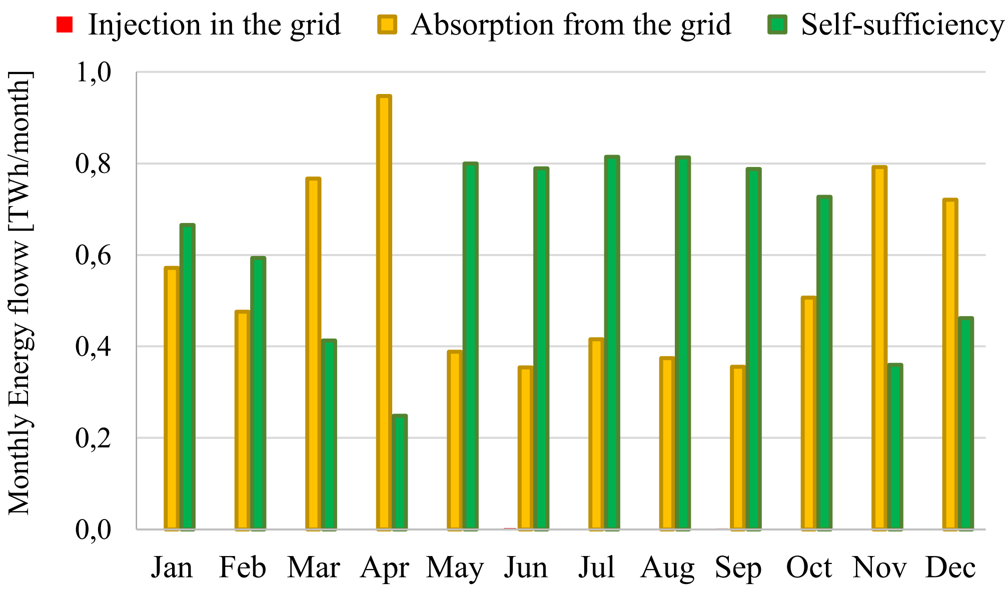

Figure 4. 28 Maximization of the economic return, annual exchanges with the grid and monthly value of self-sufficiency, Case #4

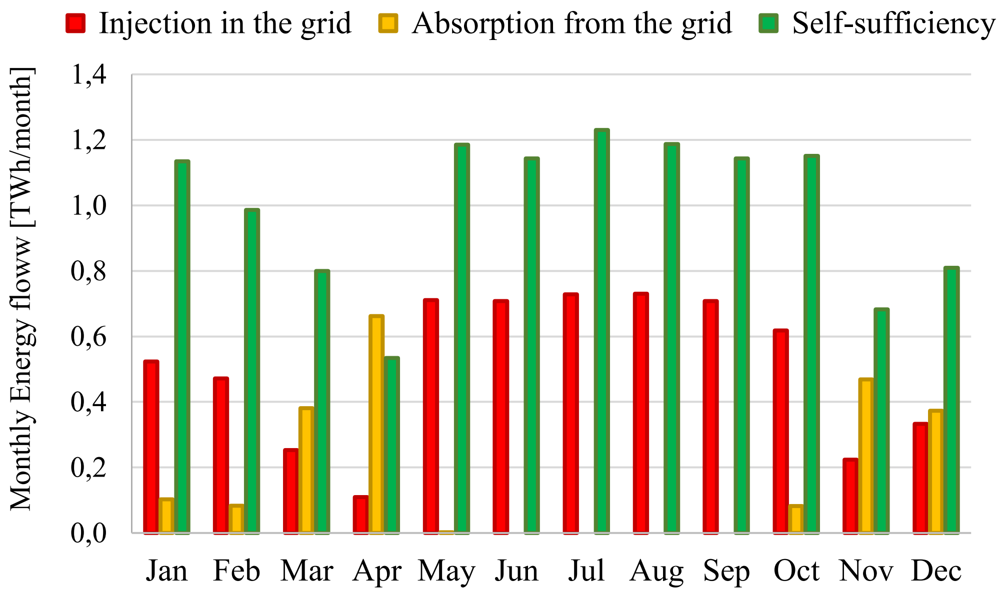

Figure 4. 29 Maximization of the economic return, annual exchanges with the grid and monthly value of self-sufficiency, Case #2

Table 4.22 shows the main data obtained from the optimization analysis performed both on the value of self-sufficiency (*Paragraph 4.3)* and in the case of the economic return on the investment performed on both the NPV and the IRR.

	Max. Self-Sufficiency	Max. NPV	Max. IRR
Size of plants			
Total power of PV generators [GW]	4.9	-	-
Total power of WT generators [GW]	2.0	2.9	1.1
Capacity of storage [GWh]	5.4	-	-
Energy flows (AC)			
Production from PV+WT [TWh/years]	17.0	18.2	7.6
Annual load [TWh/years]	14.1	14.1	14.1
Annual injection in the grid [TWh/years]	4.1	6.2	0.01
Annual absorption from the grid [TWh/years]	1.3	2.1	6.6
Main results			
Self-sufficiency	91%	85%	54%
NPV after 25 years [billion €]	4.3	12.1	5.8
IRR	16%	46%	54%

Table 4. 22 Main results of the maximization process

Chapter 5

5 Conclusions

In this master's thesis work, the optimal planning of photovoltaic systems, wind turbines and electrochemical storage was performed, taking into consideration various physical and economic constraints. In particular, the Sri Lankan case study was analysed.

First, to define the suitable sites for the installation of photovoltaic and wind systems an analysis was carried out, considering both territorial constraints and the distribution of resources by analysing data on irradiance and mean wind speed in the area. In this analysis, the proximity to the transmission and distribution grid, and the presence of electrical loads were taken into account.

The main goal is to create systems that are as independent as possible from fossil fuels. Moreover, the system must be economically advantageous with an higher return to the investment. In addition, was limited the exchange of electricity with foreign countries by imposing the constraint of 1 GW. For this analysis the site near Hambantota was analysed (Site #2): from different simulations it emerged that the optimal solution was achieved by installing 4.9 GW of photovoltaic system, 2.0 GW of wind system and 5.4 GWh of storage capacity. With these parameters, the level of self-sufficiency achieved is equal to 91% and the NPV is equal to 4.3 billion €. For this site the availability of wind resource is very high; from the weather data it is also possible to note how the number of hours in which there is at least one source between wind and solar is very high, about 98% of the number of total hours per year.

The energy sensitivity analysis was subsequently performed: in this way it is possible to analyse the effects on the project when an input parameter was varied in order to find the optimized solution and evaluate different scenarios. For this sensitivity analysis, different plant configurations were evaluated by changing the size of the generators and the storage capacity: for the Site #2, the maximum self-sufficiency value (91%) was reached when 70% of the production was generated by the wind system. Instead, the maximum NPV value, about 8 billion €, occurs in the case in which the production was satisfied only to the wind system, so, without the presence of the photovoltaic system, with a power plant of 2.7 GW and a storage system capacity of 6.5 GWh.

A sensitivity analysis was also carried out at the local level, considering some regions of Sri Lanka. In this way it is possible to observe the results according to the different distributions of wind and solar source in the area. For the Vadamarachchi site (Site #10), the distribution of the wind resource is similar to the case of site #2: the maximum value of self-sufficiency (91%) was reached with 60% of production from the wind system. Also for the other sites analysed, namely Puttalam (Site #7), Mutur (Site #5) and Badulla (Site #3) the maximum self-sufficiency value was reached with 60% production from the wind system and the maximum value found is respectively 73% , 85% and 77%. However, Site #3 has a very high annual variation of the wind source, and in this case it is preferable to install more photovoltaic systems.

Then an analysis was then performed maximizing the economic return, in particular maximizing the value of the NPV and the IRR. By maximizing the value of the NPV, an excellent economic return on investment of about € 12.1 billion and a high self-sufficiency value of 85% were obtained by installing 2.9 GW of wind power plant, without the presence of a photovoltaic generators and a storage system, which is very expensive. By maximizing the value of the IRR, the system is undersized with respect to the electrical load and the value of self-consumption is very high.

The most convenient plant is the one that allows to produce everything that is self-consumed by the country itself, avoiding the use of fossil fuels and the purchase of electricity from neighbouring countries. The solution found by maximizing the NPV is an excellent compromise between economic return and self-sufficiency value obtained, however a configuration with a more diversified portfolio was preferred due to the uncertainty and uncontrollability of renewable sources. At last in this case, the solution obtained by maximizing the value of self-sufficiency was preferred.

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