Technical University of Crete
School of Electrical and Computer Engineering

Modeling of Hybrid Operation of a Concentrated Solar Power production unit

Master Thesis

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I hope I made all of you proud.

Abstract

Concentrated Solar Power (CSP) plants are Renewable Energy Source (RES) units that gain popularity in countries with high solar radiation. CSP plants have already been installed in countries of South Europe and in the Middle East and North Africa, where relevant regulating environment has been developed. The key elements of such legislative frameworks are reviewed in this thesis. Solar dish-Stirling technology is CSP technology that can be more easily integrated into Distribution networks due to its small size. However, a disadvantage of this technology is that features shorter thermal inertia and thus, its output is more volatile compared to large scale CSP plants.

In this thesis, the injection to the grid of a solar dish-Stirling plant connected to a battery bank forming a Hybrid plant is studied, in order to determine up to what extent the production volatility and 'duck curve' reduction can be achieved. A modeling approach of the electricity output of a solar dish system combined with a lithium-ion battery, is developed. A methodology based on the minimization of the mean square error between the actual and the proposed stabilized production is presented, in order to optimally size the battery bank and reduce the power production volatility of the CSP. Also a methodology is developed to tackle with the 'duck curve' effect in providing capacity of 15% and 30% of the nominal power two hours after sunset.

Results from the operation of such a Hybrid plant for typical days of various seasons on the island of Crete prove the capability of such a configuration to provide guaranteed amount of power, along with the addition of volatility decrease and capacity credit. To foster such an operation, the principles for suggesting a new premium Feed-in Tariff system to aid the remuneration of power production at various amount of capacity credit providing 2 hours after sunset are suggested. Such a scheme takes into account the battery capacity of the Hybrid CSP, the capacity credit provided and also has a relative dependence of the fuel price used by the most expensive conventional unit. The suggested FiT acts as an additional premium remuneration alongside the remuneration for power production, to the producers that provide capacity credit to the grid, justified also by the economic benefits achieved. The Calculation of these benefits is based on simulations with actual data from the power grid operation based on optimization algorithm, for both solar-dish CSP operation alone and in Hybrid mode offering capacity credit two hours after sunset.

Last but not least, in order for the power grid operator to verify capacity credit assurance and receive information from the Hybrid plant, measuring requirements should be issued. A review of existing regulations on this issue is also made in this thesis.

Περίληψη

Τα Ηλιοθερμικά Εργοστάσια (ΗΘΕ) είναι μονάδες Ανανεώσιμων Πηγών Ενέργειας (ΑΠΕ) που γίνονται πιο διάσημα σε περιοχές με μεγάλη συγκέντρωση ηλιακής ακτινοβολίας. Πολλά ΗΘΕ έχουν ήδη κατασκευαστεί σε χώρες τις Νότιας Ευρώπης και στην Μέση Ανατολή και Βόρεια Αφρική, όπου έχουν αναπτυχθεί φιλικές νομοθεσίες. Τα βασικά χαρακτηριστικά αυτών των νομοθεσιών παρουσιάζονται σε αυτή τη διατριβή. Οι Ηλιακοί Δίσκοι- Stirling είναι μια τεχνολογία ΗΘΕ που μπορεί να ενσωματωθεί πιο εύκολα σε Δίκτυα Διανομής, λόγω του μικρού τους μεγέθους. Όμως το μειονέκτημα αυτό της τεχνολογίας είναι ότι έχει μικρότερη θερμική αδράνεια, άρα είναι πιο ασταθές από μεγάλου μεγέθους ΗΘΕ.

Σε αυτή την διατριβή μελετάται η έγχυση στο δίκτυο ενός εργοστασίου ηλιακού δίσκου-Stirling που είναι συνδεδεμένο σε μια μπαταρία, με σκοπό να καθοριστεί κατά πόσο μπορεί να επιτευχθεί μείωση της αστάθειας παραγωγής και περιορισμού του φαινομένου της 'καμπύλης της πάπιας'. Αναπτύχθηκε μια προσέγγιση μοντέλου της ηλεκτρικής εξόδου ενός ηλιακού δίσκου που έχει συνδυαστεί με μπαταρίες λιθίου-ιόντων. Παρουσιάζεται επίσης μια μεθοδολογία που βασίζεται στην ελαχιστοποίηση του μέσου τετραγωνικού σφάλματος μεταξύ της πραγματικής και της σταθεροποιημένης παραγωγής που προτείνεται, ώστε να βρεθεί το μέγεθος της μπαταρίας βέλτιστα και να μειωθεί η αστάθεια της παραγωγής του ΗΘΕ. Επίσης αναπτύχθηκε μια μεθοδολογία για να αντιμετωπίσει το φαινόμενο της 'καμπύλης της πάπιας' με το να παρέχεται το 15% και το 30% της ονομαστικής ισχύς δύο ώρες μετά την δύση του ήλιου.

Τα αποτελέσματα από την λειτουργία ενός Υβριδικού εργοστασίου, για τυπικές μέρες από διάφορες εποχές στο νησί της Κρήτης, αποδεικνύουν την ικανότητα μιας τέτοιας διαμόρφωσης να παρέχει εγγυημένη ισχύ, σε συνδυασμό με την μείωση της αστάθειας και την εγγυημένη ισχύ. Για να ενισχυθεί αυτό το είδος λειτουργίας προτείνονται τα αρχικά στοιχεία για την πρόταση μιας νέας επιπλέον Ταρίφας Τροφοδοσίας (ΤΤ) για να αποζημιώσει την παραγωγή εγγυημένης ισχύος σε διάφορα επίπεδα δύο ώρες μετά την δύση του ήλιου. Ένα τέτοιο σχέδιο λαμβάνει υπόψιν του την χωρητικότητα της μπαταρίας του Υβριδικού ΗΘΕ, την εγγυημένη ισχύ που παρέχεται και επίσης έχει μια μικρή εξάρτηση από την τιμή καυσίμου που χρησιμοποιείται από την πιο ακριβή συμβατική μονάδα του συστήματος. Η προτεινόμενη ΤΤ λειτουργεί σαν επιπλέον ταρίφα για την εγγυημένη ισχύ παράλληλα με την καταμέτρηση για την παραγωγή ενέργειας, στους παραγωγούς που παρέχουν εγγυημένη ισχύ στο δίκτυο, που έχει επαληθευτεί από τα οικονομικά οφέλη που επιτυγχάνονται. Ο υπολογισμός αυτών των οφελών βασίζεται σε προσομοιώσεις με πραγματικά δεδομένα της λειτουργίας του ΣΗΕ Κρήτης δικτύου ενός αλγορίθμου βελτιστοποίησης, για την λειτουργία του ηλιακού δίσκου ΗΘΕ με ή χωρίς την Υβριδική λειτουργία που προσφέρει εγγυημένη ισχύ για δύο ώρες μετά την δύση του ηλίου.

Τέλος, παρουσιάζεται μια σύνοψη των απαιτήσεων μετρητικών διατάξεων από το διαχειριστή του δικτύου προκειμένου να επαληθεύσει την εγγυημένη ισχύ και για να πάρει πληροφορίες για το Υβριδικό εργοστάσιο. Μια ανασκόπηση των υπαρχουσών νομοθεσιών για αυτό το θέμα γίνεται σε αυτή την διπλωματική.

1 Introduction

When it comes to Renewable Energy Sources (RES), the solar energy comes in mind as the main shareholder of the RES power production across the globe in the form of Photovoltaic panels, either in larger or smaller PV parks or even Building Integrated PVs. But there is also Concentrated Solar Power (CSP) technology that can produce electricity at a large scale exploiting also solar energy. Concentrated Solar Power is a kind of RES that produces electricity by utilizing the thermal content of solar energy via appropriate thermodynamic cycles. However, there are CSP technologies, which like PVs can produce electricity in rather small scale.

Evolving towards a society not depending on fossil fuel is becoming a matter of greater interest, as it is increasingly clear that the current energy consumption and generation trend is not sustainable, due to the exhaustion of fossil fuel resources and its effects on climate change. Thus, it is really important to employ Renewable Energy Sources (RES) that could aid provide substantial aid to meeting the evolving electricity demand when the old, fossil fuel operated units retire, presenting quite similar or even improved operational characteristics in terms of Dispatchability that other widespread RES such as wind power and PV cannot provide without aid of storage.

Concentrated Solar Thermal Power Plants becomes a popular renewable energy source technology, especially in areas that have very high solar potential such as Middle East and North Africa (MENA) countries, the countries of the Mediterranean, US and India. Also it becomes more and more popular because compared to other RES technologies, and especially the PVs, they have the capability of greater power production, higher power density (approximately 40-45% more than a PV park) and more stable output. [1]

In Table *1* the countries in the regions mentioned above, their CSP capacity as well as their future constructions and solar potential is presented.

There are currently four CSP technologies, parabolic trough collectors, solar tower, solar dish and Fresnel collectors. All of these categories have a lot of differences between them, but the main operation of concentrated the solar thermal energy and converting it to electricity is the same in all of the technologies. More details on these technologies are described in Chapter 2. There are currently 104 CSP power plants operating in the world, mainly in the Middle East, Africa Europe and USA, most of them based on the parabolic trough collector technology as shown in Figure 1. [2]

The installed nominal capacity of the CSP plants is reaching 4326 MW, with the most of them been parabolic trough collector CSPs, as shown in Figure 2**.**

Table 1: Countries with CSP penetration

Country	Solar Radiation	Operational CSP capacity (solar)	To be installed CSP capacity
Algeria	6 KWh/m^2 average daily	25 MW	250 MW (planning)
Egypt	5–6 KWh/m^2 average daily	20 MW	150 MW (on hold)
Greece	5-6 KWh/m^2 average daily		50 MW (on hold)
India	5 KWh/m^2 average daily	220 MW	80 MW (construction)
Israel	3-4 KWh/m^2 average daily	6 MW	250 MW (planning)
Italy	3.4 KWh/m^2 average daily	8 MW	150 MW (on hold)
Morocco	4-5 KWh/m^2 average daily	23 MW	450 MW (development)
South Africa	4.5-5 KWh/m^2 average daily	0.33 MW	150 (construction)
Spain	3-5 KWh/m^2 average daily	2250 MW	
USA	4-5 KWh/m^2 average daily (sunny regions)	1800 MW	

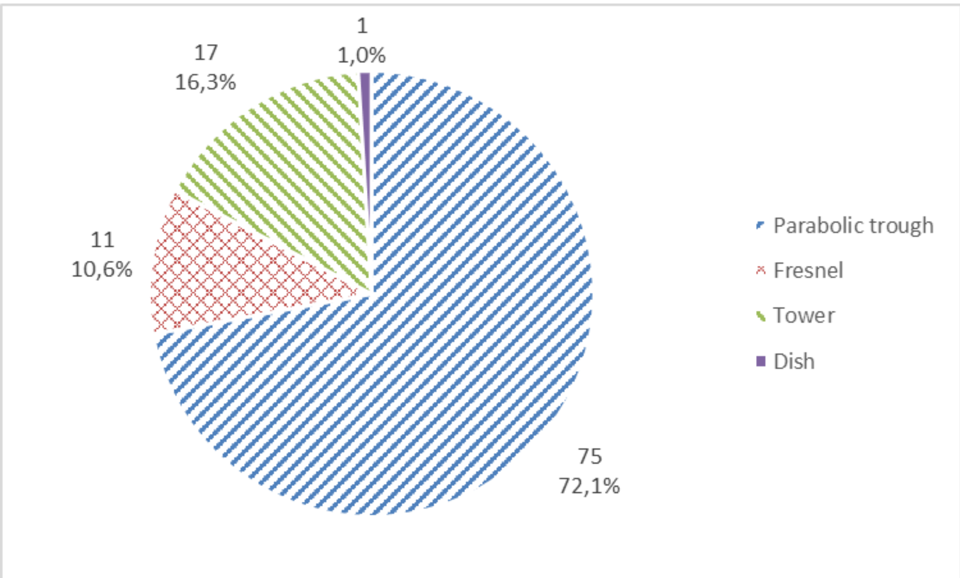

Figure 1: Operational CSP Power Plants per Technology

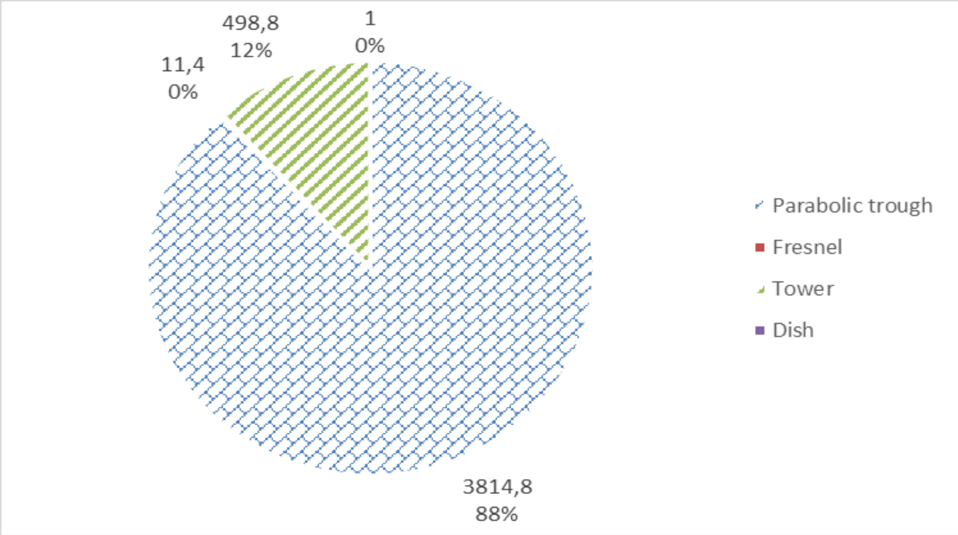

Figure 2: Operational nominal capacity of CSP plants per technology

As shown in the figure above, the vast majority of the installed capacity is based on the parabolic trough collector technology and not so much in the other technologies especially the solar and Fresnel dish. The main reason is that parabolic trough CSP plants are an older technology, more mature and can produce more energy per installed capacity than other technologies of CSP. Another reason behind this is that most of the installed parks with the solar dish and Fresnel Dish technologies were built in order to test the technology rather than produce large amounts of electricity.

It is also important to know how the CSP capacity is distributed around the world. In Figure 3 the operational capacity of CSPs based on the area they are installed is presented. Mediterranean Europe and mainly North America have the most operational CSP capacity. The reason behind this is that Spain and USA were the first countries to install vast majorities of CSPs and also to promote the technologies with appropriate regulations.

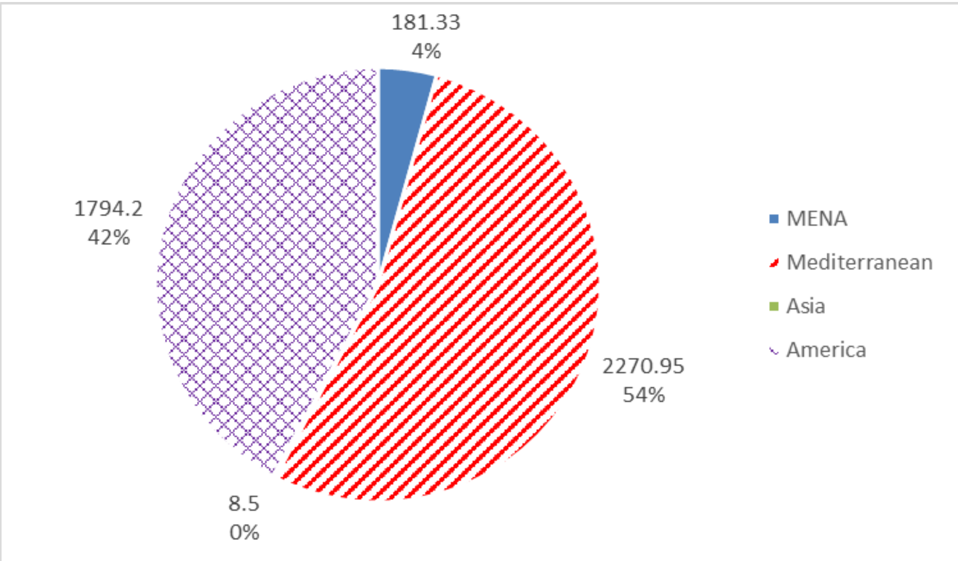

Figure 3: CSP nominal capacity per region

One of the CSP's interesting characteristics is their capability to stabilize their output with the addition of storage or extra power production from a conventional thermal unit, like in North

Africa countries. [3] Unlike other RES technologies where storage utilization is in terms of electricity only, in CSPs thermal storage can be utilized as well.

Thus, their production can be considered available to provide increased capacity credit to the upstream power system contrary to widespread Wind and PV parks, featuring the ability to effectively substitute the production of conventional power production units. This replacement is going to make the power production not only more eco-friendly but also cheaper as well in the near future. When thermal storage unit cannot be installed, like in solar dish CSPs, a conventional battery storage, like for any other case of RES can be installed to provide the extra power needed.

1.1 Aim and structure of this thesis

As CSP is a technology capable for large power production, and providing utility services, it is important to examine some facts about their operation and about the regulation that promotes the construction of CSP plants in various countries. CSP power plants with thermal storage and/or gas turbine extra power production are implemented mainly in the Middle East and North Africa (MENA) area and are steady and accomplished infrastructures. In this area and also in areas with high direct, or indirect, solar radiation around the world there are incentives and regulations that enable investors to construct CSPs and operate at high investment rate. Also in some countries, including Greece, because there are power grids in non-interconnected islands the regulation is a bit stricter as of the power production stability of a CSP plant.

The capability of CSP power plant to provide as stable production as possible is going to be examined, as well as the incentives given for CSP power plant production. Depending on the incentives given around the world, power production stability of a CSP plant can be proven more beneficial for the producer than conventional production. Bearing that in mind, all the regulation promoting construction and operation of CSP plants are going to be presented, as well as the Greek ones, in order to better examine the options and the benefits that a CSP producer may have and propose the best production strategy possible, as shown in Chapter 3.

Furthermore, the installation of CSP power plant on isolated power grids is going to be examined, and the possible different operation schedule the producer can achieve. There are plenty of island groups with very favorable DNI conditions where large scale CSP plants cannot be easily integrated. For such grids, it is critical for RES units to have as stable production as possible, in order not to endanger stability of their operation. A lot of problems can occur due to sudden power production decrease of RES units, causing even electricity cuts in certain areas of the grid that can’t be averted immediately because of the time that conventional units need to ramp-up. The inability to increase the production in short time is one of the main problems of RES that depend on sun for their production, a phenomenon in power grids that is called the ‘duck curve’ effect, explicitly discussed in Chapter 4.

Also due to power grid de-stabilization factors the CSP’s capacity is limited. This is not particularly a problem because technologies for smaller installations exist and can operate in order to provide utility services as well. Also with the addition of storage and the correct utilization of it, CSPs can act as distributed generation units, like gas turbines. Other RES units can also be distributed generation units unlike large scale CSPs that are aimed to provide base load for the grid. Keeping this in mind, the proposed CSP in this thesis is of nominal power output of 1 MW and solar dish technology, which is easier to implement and integrated in the energy mix in isolated grids like the Cretan one, the space required per MW is smaller than PV and there is not so much need for large areas and quantities of water. This CSP with a battery bank installed alongside it cannot only be integrated in the Cretan power system but also has the ability to provide utility services like stable power production and capacity credit.

In this thesis a solar dish CSP of 1 MW of nominal power is selected in order to integrate easier to the Cretan power system. Alongside the CSP a battery bank is implemented in order to provide extra power that can be used to provide various utility services. In order to test the production of the Hybrid CSP plant it is important to establish operational models of its parts. So a mathematical model for both the solar dishes and the lithium-ion battery bank is developed and presented in Chapter 5. These models simulate the real time operation of these parts considering all the real implications and limits that the materials have.

Operational algorithms are also developed in order to use the parts of the Hybrid CSP power plant as efficiently as possible towards solving the production stability issues and the 'duck curve' effect.

To examine the operation and the integration of the CSP with the battery bank simulations were made, based on the operational models that were developed, as shown on Chapter 5. The first simulation is about solving the RES production stabilization problem, which was discussed before. The results showed that a hybrid mode operation of the CSP and the battery bank can provide sufficient stabilization to enable more integration for the unit and more production reliability.

Next simulations about the CSP's ability to reduce the 'duck curve' effect are run. First a simulation for the hybrid CSP unit to produce 15% of its nominal power for two hours after sunshine is examined. Then another one that the CSP had double battery bank and also provided 30% of the nominal production for two hours after sunshine is performed. Also a simulation was run with only the CSP production without any aid of the battery bank, so as to compare the results of the ones with the implementation of the battery bank. The results of all these simulations described are shown in Chapter 7, based on actual data from our case study system, the island of Crete and are further exploited in order to propose a FIT that rewards producers for capacity credit in a more direct way than the payment method that is already active and to those that can provide capacity lower than 100% of their plant nominal power.

Results have shown that production of CSP after sunshine cannot only responsible and stable but also beneficial for the grid. This operation provides capacity credit for the grid, which in Greece is remunerated but not in hourly basis and in smaller quantity than 100% of the nominal power of the power plant. In this thesis a new way to remunerate the value of the capacity credit gives incentives to the power producers and also is beneficial for the grid as a whole is presented. The scheme that is presented is based on hourly production day by day and the capacity credit is remunerated as a premium FIT, which can be in any amount the producer can provide. Also it is also important to establish measurement systems for the grid operator to establish the capacity credit and approve the payment that is due.

Regarding all the above in this thesis, the main points of examination are summarized as follows:

- Review of Existing CSP technologies, their components and their operational characteristics
- Review of Regulations and incentives from around the world for CSP power plant construction and operation with emphasis to Hybrid CSP configurations
- Production stability issues for CSP units and 'duck curve' effect reduction
- Algorithm Proposal for reducing power production volatility of Solar Dish-Li-ion Battery installation or extending its production by a percentage and some hours to face the 'duck curve' effect in a Solar dish power plant
- Measurements on CSP operation required by regulators for the effective integration of power production in the power grid, or capacity credit verification as the one suggested in this thesis.

- FIT proposal for remuneration of specific percentage of capacity credit after the end of sunshine period based on actual data simulations and ways to calculate such FiTs or premiums in similar power systems as well.

2 Review of existing CSP Technologies

In this Chapter additional information about CSP various technologies is introduced, in order for the reader to further understand which parts comprise the CSP plants and how such plants operate. The basic and more popular types of solar thermal technologies are four: (a) parabolic trough collectors, (b) solar tower, (c) solar dish-Stirling and (d) Fresnel collectors. Each one of these technologies has its own advantages and disadvantages and can meet various applications. [4]

2.1 Parabolic Trough Collectors

Parabolic Trough Collectors is the most popular CSP technology and appears in the most installed parks around the world. Currently, there are 75 CSP parabolic trough power plants operating around the world, of total nominal power of 3.9 GW, and approximately as many is going to be constructed or are under development in the following years, of total nominal power around 1.4GW.[2] It is very common for the CSPs based on this technology to feature huge size, occupying a lot of hectares of land (around 2.500-5.000 m^2/KW), and to have high power output. Parabolic Trough power plants can easily be combined with thermal storage, or other energy storage technique, as well as with conventional, oil or coal, thermal power production units, in order to increase their power production stability, or prolong the operation hours of the power plant.

The units that comprise a parabolic trough collector solar thermal plant are:

- The parabolic collectors
- The tubes inside the collectors channel the flow of the hot-absorbent material (HCE)
- The steam turbine and the power generator
- The thermal storage unit (if it is installed)
- The burner of the fuel, usually oil or natural gas, if the plant is of hybrid mode type.

The parabolic trough collector components and their connection is displayed in Figure 4.

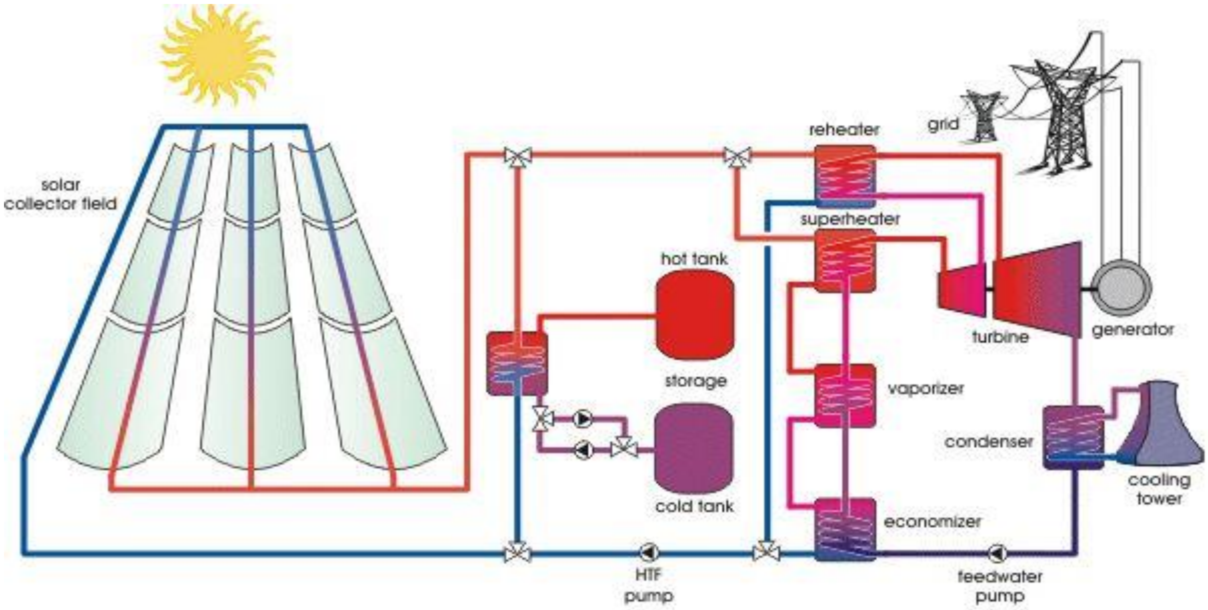

Figure 4: A Parabolic Trough Collectors type CSP.

Each parabolic trough collector, which is the most important part of the whole power plant, is comprised by the following components:

- The parabolic mirrors that are usually made by steel and covered by silver or aluminum
- The heat collection elements mounted in the focal points of the mirrors
- The frames upon which all the above are placed

The pipes that run through the parabolic collectors have diameter in the range of 70mm and length of about 4m, depending on the power plant and are made of stainless steel that is surrounded by a glass tube of around 115mm diameter with absorbing properties. The liquid mean that transfers the energy between the various points inside the CSP, is usually water, molten salts, Caloria, Hitec XL, Therminol VP-1, Hitec, Dowtherm Q and Dowtherm RP, with the first two being the ones that are used more often.

The steam turbine, in order to operate properly, must be injected with steam of temperature between 300 ^{o}C – 500 ^{o}C and pressure of 40-90 bar. The steam turbine must also have a cooling mechanism that is usually based on water or air. The water consumption of the station for cooling is 3.1-3.8 m^3 per produced MWh. The power efficiency of a steam turbine is around 30-40%. The thermal cycle that characterizes their operation is the superheated Rankine steam cycle.

If thermal storage is included, it usually increases the power production of a CSP power plant by 25-70% annually and also provides power production stability. The most popular thermal storage technology is with molten salt, consisting of two tanks that contain molten salt, one which is hot and one which is cold. There is also another thermal storage technique, the Thermocline technology using only one tank. The thermal energy capacity is designed so that the thermal storage can power the steam turbine for about 13 hours.

If an extra burner is installed, then the CSP power plant can operate with the use of fossil fuel. The burner provides to the steam turbine the extra steam necessary to operate when the solar field cannot suffice. The extra fuel burner can increase the production of the CSP depending on its operation time, but in some countries the remuneration of power production depends on the the extra fuel burner rated energy. The fuel used by the burner can be of conventional type, such as oil or biomass, depending on the installation, and the percentage of fuel use varies from country to country, as shown on Chapter 3.

The hybrid operation of a parabolic trough CSP power plant can be based on the thermal storage of the plant, or the extra burner or both. There are two ways of exploiting these facilities. The first option is to employ the thermal energy stored to produce power that is added to the total power output of the power plant. The second option is to combine the thermal energy store with the one produced by the solar park to power the generator of the plant.

2.2 Solar tower

Solar tower is also a very popular CSP technology around the world. At present, there are 20 fully operational Solar Tower CSPs around the globe, of 500 MW total nominal power, and as many as 30 are under construction or are planned to be constructed in the next years. Solar towers, as parabolic trough collectors, are often of large scale but not so high power production comparatively, and they occupy a lot of hectares of land to be installed, around 5.000-7.000 m^2/kW. The collectors of this type of CSP are also reflective mirrors that are placed on a field and all are focused to the top of the solar tower, as a general accumulating point of all the reflection possible.

The Solar Tower Technology can also operate alongside with thermal power storage, or any other type of storage, and with conventional power production units, which are powered by fossil fuel.

The elements that are comprised together to form a solar tower CSP are:

- The collectors
- The solar tower that receives the thermal energy
- The steam turbine and the power generator
- The thermal storage tanks (if they are implemented)
- The burner of the conventional fuel if the power plant operates also in hybrid mode

The Solar Tower parts and the way they are connected to form the power plant are displayed in Figure 5.

In the top of the tower there is a thermal receiver that concentrates the solar thermal energy. Inside the tower there are two tanks, one with cold and one with hot transfer material, which is usually molten salt. The receiver provides thermal energy to the salt so as to raise its temperature from 293 ^oC to 565 ^oC and transfer it into the hot tank. After that, the salt in hot tank is used to vaporize water in order to provide the steam needed for the steam generator to operate.

The steam turbine, in order to operate properly, must be injected with steam with temperature between 300 ^oC – 500 ^oC and pressure of 40-90 bar. The steam turbine must also have a cooling mechanism that is usually based on water or air. The water consumption of the station for cooling is 3.1-3.8 m^3/MWh of production. The power efficiency of a steam turbine is around 30-40%. The thermal cycle type of the operation described is of the superheated Rankine steam cycle type.

Thermal energy storage can be incorporated in this type of CSP technology too and it is also based on the two tank storage described in parabolic trough section above. The thermal energy storage is designed as to be able to power the steam turbine for about 13 hours.

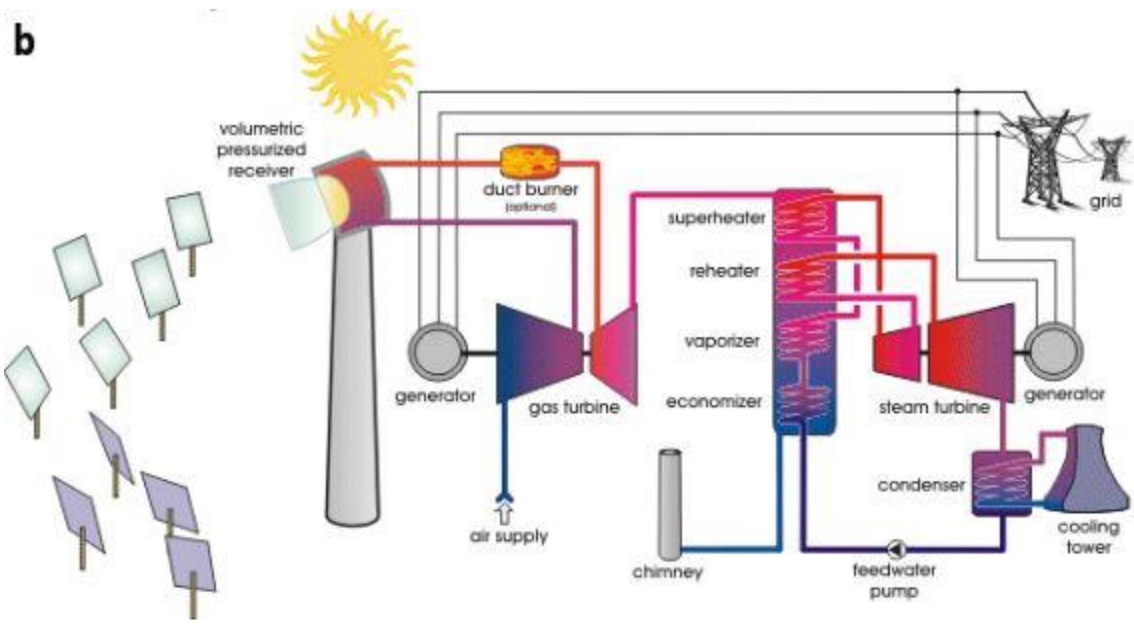

Figure 5: A Solar Tower CSP

If an extra burner is installed, then the CSP power plant can operate with the use of fossil fuel. The burner provides to the steam turbine the extra steam necessary to operate when the solar field it is inadequate. The extra fuel burner can increase the production of the CSP depending on its operation period, but only up to 20% in Greece according to the legislation. The fuel used to power the burner can be of conventional type, such as oil or biomass, depending on the installation.

The hybrid operation of such a power plant depends on whether there is storage or conventional power unit installed. The operation is identical to the parabolic trough described above.

2.3 Fresnel Collectors

The Fresnel Collectors CSP technology is the most recent technology invented for CSP power plants and it has grown popularity over the past years. Around the world there are around 10 power plants based on Fresnel Collectors, with talks suggesting the construction of more or the conversion of parabolic trough CSPs to Fresnel ones. A state of the art experimental CSP power plant is based on Fresnel Collectors, which can operate in hybrid mode with a biomass fuel generator. [2]

This technology is actually an upgrade of the parabolic trough collector technology and compared to the parabolic trough has higher efficiency, by around 10%, and almost similar power production.[5] The main difference to the parabolic trough collectors is that the thermal receiver is placed upon and not through the collectors, which enables the producer to implement also straight not parabolic reflectors and also any maintenance and operation failure can be fixed easier.

Just like parabolic trough collectors though, Fresnel collectors need room for their implementation, which increases as the power production of the plant does so, and varies around 2000-3500 m^2/KW. The main advantage of Fresnel collectors is their ability to also operate in lower power output, enabling them to be installed in isolated grids and smaller applications, applications that are residential or are about combining production of electric and thermal energy at the same time.

The elements that comprise a Fresnel collector CSP are:

- The Fresnel reflectors
- The thermal receivers
- The steam turbine and the power generator
- The thermal storage tanks, if they are constructed
- The burner of fuel, if the power plant operates also on hybrid mode

The parts comprising a Fresnel collector and the connections between them are displayed in Figure 6.

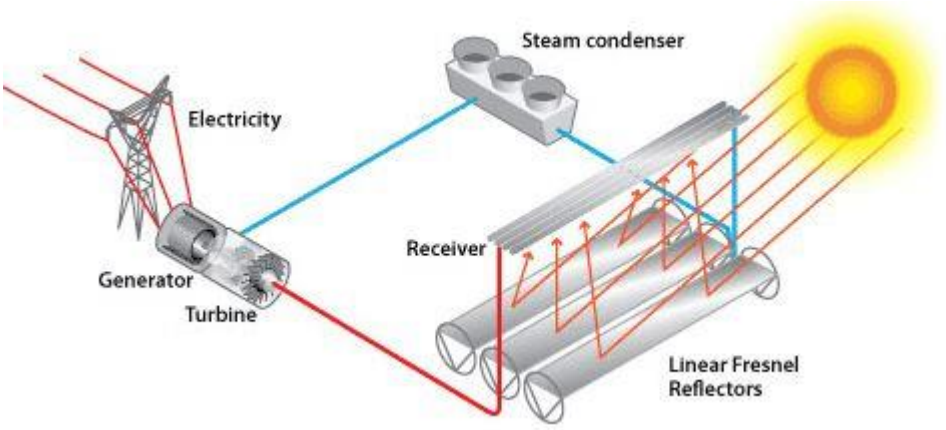

Figure 6: A Fresnel Collector CSP

In the CSP Fresnel Technology, the reflectors are also aluminum mirrors that reflect the solar radiation to the thermal receivers which are placed directly above them, in the combined focal point of the unit. The receivers are comprised by pipes, with diameter between 2-60mm, made of stainless steel and are surrounded by glass. The pipes contain the steam that needs to be heated in order to power the steam turbine. The steam is stored in a steam condenser and after being used by the turbine it returns to it.

The steam turbine, in order to operate properly, must be injected with steam of temperature between 260 ^{o}C - 350 ^{o}C and pressure of 50-80 bar. The steam turbine must also have a cooling mechanism that is usually based on water or air. The water consumption of the station for cooling is 2.5-3 m^3/MWh of production. The power efficiency of a steam turbine is around 30-40%. The thermal cycle determining its operation is of the saturated Rankine steam cycle type.

The hybrid operation of a Fresnel Collector CSP is possible theoretically and has only been tested in Italy in the Rende CSP Biomass Hybrid plant, of 1 MW nominal power. [2]

In order such a CSP to operate in hybrid mode, the thermal storage, as well as the fuel burner, need to provide to the steam turbine the steam which the solar field is not able to produce, exchanging the steam needed with the condenser, as shown in the figure above. Another operation mode is these units to only provide with the necessary thermal power the steam which is stored in the condenser and the operation of the plant continues as usual. If the second option is selected then the temperature and pressure of the steam must be at the required levels of this technology.

2.4 Solar dish – Stirling

Solar dish is a CSP technology that was invented in the 80s but was first implemented around 2000. The basic principle of this technology is the thermal power concentration by the parabolic collector as an input to the Stirling engine to fuel the power production of the unit. Operational power plants that are based on this technology are two around the world, with nominal power of

2 MW. Regarding the future construction of more solar dishes, there are some applications for the construction of such CSPs only in Greece, but are currently on hold or dismissed.

This practice is reasonable because solar dishes have lower power output than all other technologies. That characteristic is not necessarily a disadvantage, because solar dishes is the only CSP technology that can easily be integrated in housing or smaller non-interconnected grids.

Because of the low rate of production with solar dishes, the installation space needed for solar dish CSP is larger than other CSPs, due to the fact that a single solar dish CSP has around 25 KW output power, and occupies around 8000-9000 m^2/KW.

The elements that comprise a solar dish – Stirling CSP are:

- The parabolic dish or the parabolic reflector
- The thermal receiver node
- The Stirling thermal engine
- The energy storage if it is implemented

The parts that comprise a solar dish – Stirling CSP and how they are connected are displayed in Figure 7.

The parabolic collector in a solar dish is a reflecting surface that is made out of a reflective metal or glass and it concentrates the solar radiation in the focal point of the collector, where there is a receiver that concentrates the heat of the sun. The receiver is a part of the Stirling thermal engine and its main function is to prepare the heat needed for the engine operation. The output of the Stirling engine is the power output of the solar dish.

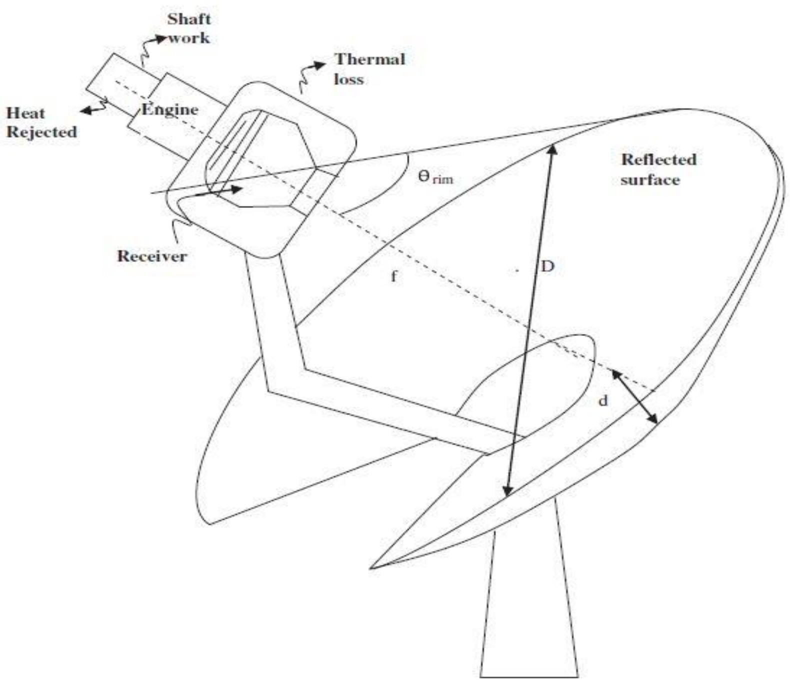

Figure 7: A solar dish - Stirling CSP

The parabolic collector in a solar dish CSP is a reflective surface made of glass or metal that can reflect well the solar radiation, concentrating the solar radiation in the focal point of the parabolic. The thermal receiver is placed on the focal point of the parabolic collector and concentrates the thermal energy of the solar radiation. There are two types of thermal receivers:

Stirling and Brayton. Stirling receivers transfer the thermal energy that is concentrated by the sun in a high pressurized gas, which is usually helium or hydrogen. The main difference in Brayton receivers, compared to the Stirling ones, is that they can operate in lower gas pressure. In both cases, the operating temperature is 500-600 ^oC.

The engine used in a solar dish CSP operates as a conventional external combustion one, which transforms the thermal energy to mechanical power. The mechanical power is used to drive the generator that produces that output electricity. The thermal cycle of a solar dish is based on the Stirling principle of operation.

The cooling devices of a solar dish CSP are different from the other technologies, because the cooling is based on the atmospheric air. Water is only used in this technology in order to clean the parabolic collectors and is rated to about 0.05-0.1 m^3/MWh. So it is important to note at this point that solar dish CSPs can also be installed in places that there is no water supply at all.

In order to achieve hybrid operation in a solar dish CSP, as mentioned for the other technologies above, there must be no Stirling engine at the focal point of the receiver, but to be replaced by a thermal transfer unit, as shown in Figure 8.

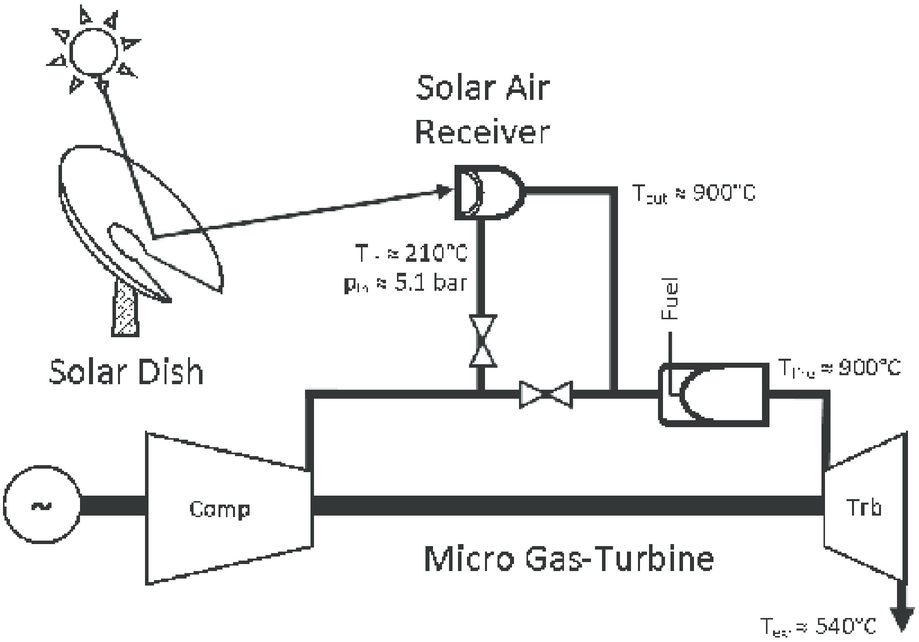

Figure 8: A solar dish with transfer of heat

This composition of a solar dish-Stirling power plant with thermal transfer is only theoretical, because other CSP technologies, as parabolic trough collectors, have higher performance in this mode, by around 30%. Because of the low performance of this solar dish technology, this technology has evolved as described at the start of this paragraph.

The solar dish Stirling CSP technology which is considered in the present work can also operate in hybrid mode, utilizing battery storage. It is easy to install, alongside to a solar dish CSP, a battery storage unit aiming to provide the necessary energy to stabilize the power output of the CSP or prolong its operational hours beyond the sunset.

2.5 Summary of CSP Technologies

In Table 2 there is a comparison of the expenses, as well as the land area needed, between all CSP technologies.[4] [6] Also in Table 3 there is a summary of all CSP technologies and their advantages.

Table 2: Installation cost and land for CSP technologies

	Parabolic Trough	***Solar Power Tower***	***Dish Engine***	***Fresnel***
Typical Capacity (MW)	10-300	10-200	0.01-0.025	10-200
Operating temperature (^{0}C)	300-500	300-500	500-600	260-350
Cycle	Superheated Rankine steam cycle	Superheated Rankine steam cycle	Stirling	Saturated Rankine steam cycle
Water requirement (m^3/MWh)	3.1-3.8	3.1-3.8	0.05-0.1	2.5-3
Energy Cost (€/kWh)	0,15-0,25	0,14-0,22	0,12-0,18	0.12-0.15
Installed Cost per Capacity (€/kW)	3500 - 7000 (with storage)	3000 - 5000 (with storage)	3000 - 4000	2500-5000
Total Land Area per MW (m^2/MW)	2500 - 5000	5000 - 7000	8000 - 10000	2000-3500

Table 3: Summary of CSP technologies

Technology	Parts	Hybrid mode	Advantages
Parabolic Trough	• Parabolic reflectors • Thermal receivers • Steam turbine	• Thermal storage • Conventional Fuel generator	• High Power production • Tested and proven technology • Thermal hybrid mode implementation
Solar Tower	• Solar Reflectors • Thermal receiver at top of tower • Steam turbine	• Thermal storage • Conventional fuel generator	• High Power production • Tested and proven technology • Easier hybrid mode implementation
Dish Stirling	• Parabolic collector • Thermal receiver • Stirling engine	• Energy storage (batteries) • Thermal storage (limited)	• Lower power output • Easier integration in isolated grids • Hybrid operation with batteries
Fresnel	• Solar reflectors • Thermal receivers • Steam turbine	• Thermal storage • Conventional fuel generator	• High power output in smaller space • Can be integrated for large or small applications • Higher efficiency factor

3 Operation regulations of CSPs around the world

The importance of establishing CSP power plants is beyond doubt, but power plants of this size are really expensive to construct, as was shown in Chapter 2, Table 2. For this reason, regulatory authorities and governments around the world try to specify the most appropriate incentives that would allow corporations, companies or utilities to build and operate CSP plants making such an investment viable within reasonable time.

In Paragraph 3.1 the generic outline of typical incentives that can be provided to RES is exposed, while in paragraph 3.2 are deployed the incentives provided to CSP in various countries depending on:

a) The utilized technology (see chapter 2)
b) The allowance of fossil fuel participation
c) The allowance of using thermal or other means of storage are thoroughly described and
d) If the power grid is isolated or not

In this thesis the regulations and policies for RES promotion around the world, and specifically the ones that refer to CSP promotion and development, are mentioned. There is a lot of countries that have implemented policies for the promotion of CSPs as presented in the following paragraphs of this thesis. Also lots of countries include CSP units in generic RES regulations and are mentioned in this section.

The vast majority of the implemented policies are feed-in tariff schemes mainly because these are tested policies and have positive and immediate results. Regarding CSP power plants, these incentives have also variations depending mainly on the approach each country has for the promotion of RES. This approach also contemplates on CSP power plants technologies and operation modes that is why in some countries a lot of plants that support cooperation are also included in these schemes as well as power plants that have any kind of storage. In this Section, only already implemented policies for CSP plants are presented.

3.1 Generic Promotion Practices for RES

As mentioned before, the importance of establishing CSP power plants is beyond doubt, but power plants of this size are really expensive to construct. Regulators around the world provide a lot of schemes that give investors incentives to construct these types of power plants and make such an investment viable. In this section an overview of policies implemented or proposed, for the reasons mentioned above, are presented.

3.1.1 Feed in Tariff

Feed-in-Tariffs (FiTs) refer to the regulated minimum guaranteed price per KWh that a Market Operator has to pay to a private, independent producer for electricity injected to the grid. In other words, FiTs refer either to establishing that all the produced power from renewable energy sources is being purchased or the energy price that is paid by the consumers is increased or both. This tariffs incentive, acknowledged for a fixed time period, usually 10 to 20 years, awards plant efficiency and it generates a shorter payback time for individuals and companies investing in RES units connected to the grid. Such a mechanism has been introduced in all European countries, first of all in Germany and had so much success that was accumulated by other countries, and to North Africa countries like Algeria. [7]

3.1.2 Net metering

Net metering is a service to an electric consumer under which electric energy generated by that electric consumer from an eligible on-site generating facility and delivered to the local distribution facilities may be used to offset electric energy provided by the electric utility to the electric consumer, during the applicable billing period. Net metering can be implemented by using a bi-directional meter than accounts the electricity that is absorbed by the grid and the electricity sold to the grid and accounts the energy bill of the consumer from these readings. This scheme is really flexible and applicable to any grid connection and especially small house oriented power producers, in an attempt to keep the energy production organized and cheap. [7]

In order to better understand this scheme a net-metering configuration is presented in Figure 9.

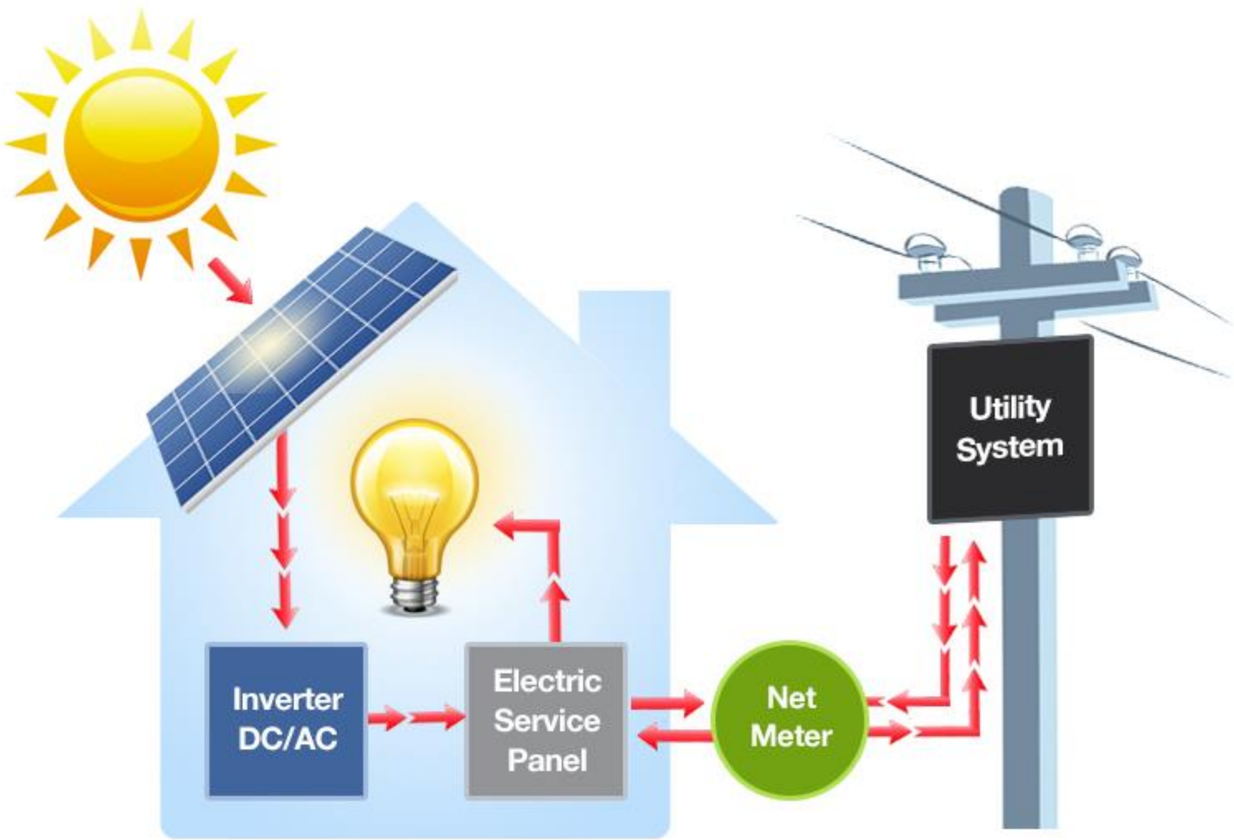

Figure 9: Net-metering scheme

3.1.3 Tax credit

Tax credit or tax relief is a public measure providing specific investments with a tax allowance. This funding scheme is usually suggested by governments or by intergovernmental organizations and is usually a law. Such scheme makes investments on RES eligible or the amount of allowance that the investor has. In some cases, having tax reliefs for RES investments indicates the concern of the country on the climate change, or to increase the public awareness to this subject.[7]

3.1.4 Loan

A public loan can be defined as a public authority lending an amount of money to another subject who pays it back in periodical installments, including a capital share and an interest share. The difference between this and a loan given by a private sector is that the interest rate is considerably lower, maybe zero, and it aims to improve the RES infrastructure of the country and improve their power grid. Loans can be combined with grants in order to give companies more incentives in order to invest in RES technologies. Establishing such a combination can provide a starting capital for the investment and the funds necessary to complete the project. [7]

3.1.5 Capacity Credit

Unlike the first two incentive schemes that focus on the energy injected to electricity grids, incentives can be provided for increasing the reliability and dispatchability of a Power System. Under such circumstances and based on the fact that CSP units could provide substantial aid for serving this purpose, incentives legislation may additionally consider Capacity Assurance Remuneration for the Guaranteed capacity to the grid. This specific policy gives incentives to producers to build CSP plants with thermal storage or external thermal unit, so as to have a more stable and guaranteed production. Also by this policy more efficient CSP plants are built with external energy production and careful planning of the production.[7]

3.1.6 Tender framework

There are a lot of countries around the world, but especially in the MENA region, that have the intention and offer the required legislation in order to promote the construction of CSP projects. What they lack is the funding in order to implement the projects they have in mind. In order to attract potential investors in the field each agency provides a group of experts in order to provide the necessary studies and guide the investors through making the best investment according to the needs of each country. This scheme can attract investments from companies than only have a budget to invest and not the necessary infrastructure to implement that type of projects. Furthermore, it enables governments and policy makers to overview the construction of the facility and makes them sure that it is going to be completed as planned and they don't have to spend more money doing so. Tender framework can be easily implemented in co-operation with all the other schemes and provide better results than expected.[8]

3.1.7 Clean Development Mechanism

The Clean Development mechanism (CDM) is one of the schemes adopted by the Kyoto Protocol in order to promote emission reduction projects. Under the United Nations Framework countries that are in the UN or not and are classified as developing countries, as non-Annex I countries, can seek for a budget that is going to be invested in creating projects that prevent the climate change. So the countries that as classified as Annex II by the UN can apply for a grant in order to construct RES projects in their area and gradually replace their old emitting power production units. The amount each country gets depends on previous grants it may have taken and the economic situation in the country.[8]

3.1.8 Tradable Green Certificates

Another notable mention, that is starting to take point in policy making, is the Tradable Green Certificates. In tradable green certificates systems, electricity generated by RES is sold in the electricity market at market prices, while these are also corresponding to certificate trading in a separate market for green certificates. The buyers, who are either electricity producers or consumers, are obligated to buy certificates corresponding to a certain quota of their total electricity sales or consumption. This is a suggested policy yet to see if it is going to be implemented.[8]

3.2 Energy Markets

In the previous section the various policy incentives are presented. In this section the implemented policies in countries around the world, regarding CSP is presented. It is important to mention here that other countries have implemented policies for RES units, but in this section only the countries that have specific policies for CSPs are analyzed.

Despite the countries that have specific regulations for CSP, which are mentioned below, there are also countries that implemented policies for RES units, especially for solar powered ones. These policies can also be applied for CSP units as well, if they meet the criteria mentioned in those policies, if there is not any specific mention for them. These countries are presented in Table 4.

Table 4: Other RES policies

Country	Policy	Description
Germany	Feed-in-tariff for PV only	<10 kW 12,88 c€/kWh 10-40 kW 12,22 c€/kWh 40kW - 1MW 10,9 c€/kWh 1-10 MW 8,92 c€/kWh
USA California	Feed-in-tariff <=10 MW demonstration	Solar projects 12,36 - 14,003 c$/kWh
Cyprus	Feed-in-tariff solar	0,26 €/Wh for 20 years Financial incentives Subsidies on capital cost and license acquisition cost Support in cost of ancillary services
United Kingdom	Feed-in-tariff solar PV	6,38 - 13,88 p/kWh (pounds)
Egypt	Feed-in-tariff RES	households 0,101 €/kWh < 200 kW 0,109 €/kWh 200 - 500 kW 0,117 €/kWh 500 kW - 20 MW 0,118 €/kWh 20 - 50 MW 0,123 €/kWh > 50 MW government contracts
China	Feed-in-tariff solar	0,15 €/kWh
Australia	Net metering	Measure the amount of RES electricity that is absorbed by the grid
	RES	Pay 0,25 c$/kWh
Switzerland	Feed-in-tariff Solar PV	0,33-0,44 $/kWh
Thailand	Feed-in-tariff solar	27 c$/kWh for 7-10 years
Uganda	Feed-in-tariff solar PV	0,362 $/kWh for 20 years
Ukraine	Feed-in-tariff solar	0,48 €/kWh

At this point, it is important to mention the improvement in the CSP industry that has been made in Egypt and Morocco, which provide tender framework for CSP promotion and implementation and have implemented CSP power plants in their region.

Morocco has an established policy to provide electricity in rural areas utilizing PV installations. Also the Centre for the Development of Renewable Energies (CDER) was established in order to overview the production of RES units in the area and provide the framework necessary to promote the installation of larger capacity of RES. Morocco has the first Integrated Solar Combined Cycle (ISCC) unit that is constructed in the area of Ain Beni Mahar. Its overall capacity is 400 MW, of which 20 MW come from the solar field. This power plant contains a Combined Cycle unit that can be powered by natural gas and solar at the same time. [9]

Egypt, as well as Morocco, has established the New & Renewable Energy Authority (NREA) that has proposed a new electricity law to promote RES installation across the country using subsides, which help to reduce the gap between conventional units and RES. Due to internal problems in the country those actions have stopped but are now being restarted. Egypt also has an ISCC power plant in the Kuraymat site that has a 120 MW nominal power with 20 MW of solar. The power plant consists of the Combine Cycle unit that is powered by oil which power production is added by the solar field. [9]

3.2.1 Algeria

Algeria is the largest country in the North Africa region and a country among the ones with the highest solar radiation rating in the world, with daily average radiation 6000 Wh/m^2. Apart from that, studies also show that Algeria has the highest long term land potential for the installation of CSP power plants. Additionally to the above, Algeria is abundant in natural gas and oil as natural resources, Algerian government, and more specific the Agency for the Promotion and the Rationalization of Energy Use (APRUE), [10] needed to establish laws to promote the production of RES units, taking into account their rich natural resources. For this reason, incentives are given for the production of electricity by plants that combine CSP plants with additional production using Natural gas. [11]

For electricity generated from solar or radiant heat only, the bonus is 300% of the price per kWh of electricity delivered to the market operator defined by Law 02-01 of 22 Dhu El Kaada 1422 corresponding to 5 February 2002 until the minimum contribution of solar energy represents 25% of all primary energy. For electricity generated from facilities using solar thermal systems solar-gas hybrid, the bonus is 200% of the price per kWh if the solar production percentage of the plant is between 25% and 100%. If the solar production percentage of the plant is lower than 25% then the bonus is 100%-180% of the price of KWh depending of the percentage. More details for this scheme are shown in Table 5. [12]

Table 5: Algerian incentives for CSP promotion

Solar share	Bonus
100%	300%
25% - 100%	200%
20% - 25%	180%
15% - 20%	160%
10% - 15%	140%
5% - 10%	100%
0% - 5%	0%

The electricity tariffs are regulated by the CREG (Gas and Electricity Regulatory Commission). According to their latest decision, the electricity tariff is

- 0.02 €/kWh for a consumption which is lower than 41.6 kWh/month.
- 0.04 €/kWh for a consumption which is higher than 41.6 kWh/month.

The feed-in tariff provides bonuses for electricity generated by cogeneration of 160%, taking into account thermal energy use of 20% of all primary energy used. The bonuses for solar generated electricity and cogeneration are cumulative. Remuneration of the generated electricity is guaranteed over the whole plant lifetime. Under this scheme a state of the art 150 MW Integrated solar combined cycle (ISCC) has been built in Hassi R'mel and three others of nominal power of approximately 250 MW are announced and expected to be built. The Hassi R'mel is a great example of mixed production in a CSP power plant. For the electricity production, a 25 MW parabolic trough park is combined with a Combined Cycle Unit running on natural gas. This practice not only secures the electricity production of the power plant but also minimizes the investment and also the CO_2 pollutants. [2]

3.2.2 South Africa

South Africa is a country that also has great solar radiation levels. With an average of more than 2500 hours of sunshine per year and average solar radiation levels range between 4.5 and 6 KWh/m^2, there is a lot of ground for CSP Power Plants development. Based on the above, the South African authorities have made a lot of suggestions for legislation in order to help investments in the area grow.

South Africa's National Energy Regulator (NERSA) [13] announced on 31st March 2009, a system of feed-in tariffs designed to produce 10 TWh of electricity per year by 2013. The tariffs were substantially higher than those in NERSA's original proposal. The tariffs, differentiated by technology, were to be paid for 20 years. NERSA said in its release that the tariffs were based on the cost of generation plus a reasonable profit.

More specific, the feed-in tariff proposed for CSP Power Plants has an alteration for plants that have storage capacity. The electricity generated from CSPs without storage is about 0.15 €/KWh and from CSPs with at least 6 hours of storage is 0.14 €/KWh. Except for promoting CSP plants construction, South African regulators wanted also to ensure that the CSP power plants that are going to be constructed to be state of the art CSPs with storage that can enable the power plants to produce electricity even if there is no sun, and also provide some auxiliary services. As this feed-in tariff was an expensive policy for the South African government was quickly abandoned and replaced by a different system.[12]

The scheme that replaced the feed-in tariff was a competitive bidding process launched on 3 August 2011. Under this bidding process the South African government hoped to achieve a more efficient payment system than before and also still expand the RES facilities across the country. The bidding process comprised two steps:

- Qualification phase. Projects are assessed based on structure of the project, legal, land acquisition and use, financial, environmental consent, technical, economic development and bid guarantee.
- Evaluation phase. Compliant bids are then evaluated based on: (1) price relative to a ceiling provided in bid documentation, accounting for 70% of the decision, and (2) economic development, accounting for 30% of the decision. [8]

This scheme is now active and is expecting new entries until June 2016. Now the only operational CSP power plants in South Africa are an experiment on Fresnel solar dish technology of nominal power of 0.33 MW and a 100 MW parabolic trough with 10 hour storage. [2]

3.2.3 India

India is one of the countries in south Asia with very high solar radiation levels. The country's average solar radiation level per day is around 5 KWh/m^2. India's state structure is quite similar to the USA, having a federal government alongside with separate region's governments. So in India a federal feed-in tariff is established but also each separate government may also have different policies.

The main feed-in tariff scheme, which is established for all the interested regions, gives a lot of incentives to CSP owners. The price that the CSP electricity production is going to be paid is 0.342 €/KWh, which is one of the highest tariffs in the world. Except for that, the states Nadu, Karnataka and Pradesh have a running net metering system. This system is a net-metering scheme and the producers are paid for the amount of electricity their CSPs inject to the grid. The local regulators are currently thinking of changing the federal feed-in tariff law in order to reduce the running costs of the country.[12]

All the regulated schemes resulted in the construction and operation of slightly more than 180 MW of CSP power plants, most of them are built in the Rajasthan region.

3.2.4 USA Hawaii

The USA state of Hawaii has one of the highest solar radiation levels in the country. The Hawaii state has about 3500 hours of sunshine in a year, with an average solar radiation around 5.6 KWh/m^2. In order to exploit this solar radiation potential, the state government of Hawaii has established regulations so as to attract potential investors in the field.[15]

The Hawaii Public Utilities Commission and the Hawaiian Electric Company established a feed-in tariff scheme but for small CSP power plants. The price of electricity for CSPs with nominal power lower than 20 KW is either 26.8 c$/KWh and 35% state tax credit or 33.1 c$/KWh with 24.5% refundable tax credit. The tariff for CSPs with nominal power greater than 20 KW is either 25.4 c$/KWh with 35% tax credit or 27.5 c$/KWh with 24.5% refundable tax credit. A summary is shown in Table 6.

This scheme can also be supported with the federal incentive that the US federal government gives. US federal government gives owners of CSP low tax loans and extra tax incentives if they decide to invest in RES development. Furthermore it is shown that the state of Hawaii is aiming to build small CSP power plants, maybe depending on the solar dish technology, because the space required to build larger CSPs is not available in this state. [12]

Table 6: Feed-in tariff scheme in Hawaii

Size	**Price**	**Extra incentives**
CSP < 20 KW	26.8 c$/KWh	35% tax credit
	33.1 c$/KWh	24.5% refundable tax credit
CSP >20 KW	25.4 c$/KWh	35% tax credit
	27.5 c$/KWh	24.5% refundable tax credit

The only operational CSP plant the state has is located at Holaniku. This CSP is a small one with nominal power production of 2 MW and it is based in the parabolic trough technology. It was the first power plant that the National Renewable Energy Laboratory of Hawaii in 2006 and it was constructed to prove that micro-scaled CSPs can also be effective and produce the electricity needed depending of the region. It is important to be noted that the regulation as it is now favors the production of solar dish CSP power plants, more than anywhere in the world. [2]

3.2.5 Spain

Spain is another example of a country with favorable solar potential, between 3000-5000 Wh/m2 with the highest values it the southern parts of the country in the Andalusia region. [14] [13] Spain officials and interested parties were one of the first in Europe to organize a feed-in tariff system in order to help all of the stakeholders in all Spanish regions to start engaging CSP projects. The implementation of the feed-in tariff resulted in the construction of 49 CSP power plants with nominal power of 2254.9 MW, which are now operational.

Spanish feed-in legislation was set by Royal decree 1578/2008 (Real Decreto 1578/2008), for photovoltaic installations, and Royal decree 661/2007 for other renewable technologies injecting electricity to the public grid [16] . These legislations gave CSP owners two options. The first option is to sell the electricity produced at a fix price of 0.28 €/KWh for the first 25 years of the operation of the CSP power plant and from then on at 0.23 €/KWh. The second option is to participate in the organized electricity market, already in operation, in which they can sell the electricity produced within a range of prices. The maximum price that can be achieved with this scheme is 0.36 €/KWh and the lowest price is 0.26 €/KWh. If the CSP power plant is used also for heat production then the feed-in tariff is 13.29 c€/KWh for all the lifetime of the system. A summary of all the regulated feed-in tariffs of Spain for CSP power plants is shown in Table 7. [12]

Table 7: Feed-in tariff for CSP in Spain

Option	Price	Period
Regulated tariff	0.28 €/KWh - 0.23 €/KWh	first twenty-five years premium price
Organized electricity market	0.26 €/KWh up to 0.36 €/KWh	lifetime of the system
Cogeneration	13.29 c€/KWh	lifetime of the system

On 27 January 2012 the Spanish government temporarily stopped accepting applications for projects beginning operation after January 2013. Operation of existing projects was not affected, but construction of new project was stopped. Because the country's electrical system had a 24 billion Euro deficit the Spanish government added a 6% tax on the revenue of all existing feed-in tariffs. [2]

3.2.6 Portugal

Portugal is another example of a European country with great solar radiation, as of course their neighbor Spain. Their average solar radiation is between 4-6 KWh/m2 which is one of the highest in Europe and is a very high rating worldwide.[17] Behind all of this solar potential Portuguese regulators were the first to establish a feed-in tariff system to promote RES development that takes in account the technology, the environmental aspects and the inflation rate through the index of prices to the consumer.

The current feed-in tariff scheme was established under the Decree-law 225/2007, which was implemented to the previous law for tariffs for RES. This scheme suggests that electricity produced by CSP Power Plants is remunerated at 26.3 - 27.3 c€/KWh, depending on the exact location of the power plant, and it is valid for 15 years. These scheme seems promising, but is only oriented towards small scale CSP Power Plants that have nominal capacity below 10 MW.

Furthermore, Portuguese regulations gives also tax incentives and subsidy payments, if there is a loan involved in the construction of the CSP power plants. The regulation not only provides CSP owners an approximately 3% tax reduction for their production but also subside their payments to the loans they make have taken, or make their payments towards the state tax free. It is clear that Portuguese regulators are aiming to develop smaller CSP power plants spread across the country, a goal that is favoring the CSP solar dish technology. [12]

3.2.7 Italy

Italy is another European country in the Mediterranean region with high average solar radiation of 3.4 KWh/m2. At the south parts of the country the solar radiation reaches approximately 5 KWh/m2. The Italian regulator authority established a feed-in tariff in February 2007 that was changed again in 2011. With this feed-in tariff Italy was the second largest country in solar PV capacity in Europe (7128 MW), second only to Germany (7500 MW).[18]

Regarding CSP power plants the feed-in tariff in Italy gives the owners gives great incentives for selling the electricity produced. There is a discrimination about the solar share of the production that the power plants has: if the solar share is more than 85% of the production, the price of electricity produced is 0.32 €/KWh, or if the solar share is between 50%-85%, the price of electricity is 0.3 €/KWh and, last, if the solar share is below 50%, the price of electricity is 0.27 €/KWh. A summary of this option can be seen at Table 8. The two options cannot be combined.

Table 8: First option of Italian feed-in tariff

Solar share	**Price**
> 85%	0.32 €/KWh
50% - 85%	0.3 €/KWh
< 50%	0.27 €/KWh

The second payment option is based on the aperture area the CSP plant occupies. If the aperture area of the plant is bigger than 2500 m^2 then the price is between 27 and 32 c€/KWh, depending on the size. If the size of the plant is smaller than 2500 m^2 then the price is between 30 and 36 c€/KWh depending on the final size. A summary of this option can be seen at Table 9.

Table 9: Second option of Italian feed-in tariff

Size	**Price**
> 2500 m^2	27-32 c€/KWh
< 2500 m^2	30-36 c€/KWh

In Italy, as in Algeria, the construction of CSP power plants that support cogeneration within the CSP with a diesel unit or a gas turbine is promoted. This scheme provides steady electricity to the grid and so the CSP power plant can produce electricity even without solar power. Also this feed-in tariff scheme has a yearly price reduction of 5% and the reduction is stopped after the tariff reaches the leveled electricity prices, which is approximately 23c€/KWh.

Regarding cogeneration, Italy was the first country to install, even for experimental purposes, the first CSP power plant with cogeneration with a biomass powered turbine. [2] The power plant has nominal power output of 5 MW and is a state of the art Fresnel collectors CSP that utilizes the production from a biomass burner to aid or stabilize its production.

3.2.8 Greece

Greece features the highest solar potential among the European Countries, along with the longest hours of sunshine. Having more than 3500 hours of sunshine a year and solar radiation level at 5-6 kWh/m^2 per day, it is important for Greek regulators to find ways to promote RES development in the country, especially the solar ones,. There is a complexity regarding regulating in the energy sector in Greece, because Greece has 32 Autonomous Power Systems installed in the Aegean Islands. [19]

Regarding CSP power plants, Greek regulators have not only tried to attract investments but also have tried to build a capacity credit mechanism in order for investors to start building state of the art, with storage to provide extra power generation by a conventional unit CSP power plants.

Currently in Greece there is a feed-in tariff scheme that also gives extra credit for capacity. Electricity produced by CSP power plants is valued at 264.85 €/MWh. If the CSP plant has a system to enhance CSP production and can reach its nominal power value for at least two hours per day, then the price of electricity produced is 284.85 €/MWh. The system that the producer can use to enhance its production, or to produce electricity even when there is no sunshine, can be either a storage system (thermal or electricity) or a generator that uses conventional fuel or biofuel. Regarding the use of a generator that runs on fuel, its nominal power depends on the nominal power of the solar production of the CSP power plant and it can only be a percentage of this power. Furthermore, if the electricity produced by the supportive generator in one year is more than 15% - 20% of the electricity produced by the CSP plant, then the producer is going to pay sanctions that depend on how much the production exceeded this percentage. It is important that from August 2012 there is an extra taxation on feed-in tariffs, because of the ongoing economic crisis in Greece.

In equation (1) the formula to calculate the aforementioned sanctions is presented.

$$CEFCL = QEFCL \times UCEFCL \qquad (1)$$

where:

$CEFCL$ – The fine in Euro

$QEFCL$ – is the quantity of electricity production that is produced in the solar thermal power station from conventional units that exceeds the 20% limit

$UCEFCL$ – is the charge for exceeding the fuel limit consumption (€/MWh)

A summary for this policy is shown in Table 10.

Table 10: CSP policy of Greece

Scheme	**Requirements**	**Price €/MWh**
CSP	none	264.85
CSP 2 hours nominal power production	supportive electricity production mechanism	284.85

There are entrepreneurs, who are interested in building CSP power plants in Greece. The parties involved have already submitted the papers required to obtain the required permission to produce electricity at the Regulatory Authority for Energy (RAE). The submissions that are submitted to the RAE and those that RAE has approved are displayed in

Table 11. It is important to note here that all the projects submitted are on hold after the RAE approval because of the RES overcapacity in isolated grids and due to the economic crisis. [20]

Table 11: CSP projects in Greece.

Area	Capacity of Submissions (MW)	Capacity of approved submissions (MW)
Islands of Greece	484.7	243
Mainland of Greece	392.1	170.6

3.3 Capacity Markets

Apart from the energy markets around the world that were displayed in the previous paragraph, another way for producers to participate in the energy generation mix is the participation in capacity markets, without excluding them from other payment schemes too. Capacity markets have been introduced in a number of countries, mainly in Europe.

Traditionally in any power grid in the world, the firm capacity was mainly provided by fuel powered units with significant nominal power output, which provide the highest stability possible, but may also have really long startup times. Gas turbines are also used to provide firm capacity but they have really expensive operation. Currently, RES technologies have also developed mechanisms to support significant and stable power output and thus enabling them to provide aid to the capacity mechanism. Regarding CSPs, the production stabilization and large power output is more common than on other RES technologies, enabling them to participate easier and almost in the same terms as coal powered units to the capacity market.

However, studies have shown that CSP power plant, especially when they utilize thermal or energy storage or cogeneration by a conventional fuel generator, are more than capable to provide capacity credit for the power grid, for at least some hours of the day.[21]

Unfortunately, but mainly because the production stabilization through storage or cogeneration is a very new concept, the CSP units, or any other RES unit, were not enabled or considered to participate in capacity market. As was mentioned in chapter 3.2.8, Greece was the first country in the world to suggest such a scheme, mainly because of the high demand of RES installation on non-interconnected islands. Non-interconnected islands, mainly in Greece, have high potential for RES penetration capacity and high potential for RES power production so the conditions are optimal for capacity production for CSP units. Currently capacity credit may be provided by rented units and expensive gas turbines.

However, in most of the cases of capacity credit mechanisms, the capacity in the power grid is provided by companies or producers via closed contracts that can last a couple of years. In countries like Spain and some more, the capacity to the grid is provided by the public electricity producer (like PPC in Greece) and there is not yet a market for capacity credit. In this section capacity markets in three countries are going to be presented, with bearing in mind that CSP units that operate in hybrid mode can also provide capacity credit in power grids. [22]

3.3.1 Greece

The Greek electricity market regulatory framework has adopted a capacity obligation scheme since 2005. According to that scheme, suppliers representing consumers (or exports) are obliged to submit to Transmission System Operators available capacity certificates, depending on the consumption profile of their clients during system’s stressed hours. Such certificates are issued by dispatchable generation units proportionally to their actual available capacity. The scheme is actual a decentralized bilateral trading of capacity certificates between suppliers and generators. However, due to the high concentration in the Greek retail market (the incumbent still has around 75% market share in retail) this scheme would practically not work and that is why it has been replaced by a transitional capacity payment scheme. This payment scheme was market-wide and was implemented from 2005 to 2014. The certificate price charged to suppliers varied from 35.000 Euro/MW-year to 56.000 Euro/MW-year during that period.[22]

Nowadays, the Regulator has proposed, in cooperation with DG Comp, a new direction for the capacity market, i.e. remuneration of flexible dispatchable units instead of market-wide payments. The new direction would be implemented in a two-phase process. The first one would last just 10 months (during 2015) and foreseeing fixed payments flexible dispatchable units, including RES units with stable power output, of 45.000 Euro/MW-year.

Up to date neither the short first-phase has been implemented nor any step towards the design and implementation of the second phase has been announced. So the existing scheme in Greece is still the one that was active between 2005 and 2014 and the charges were 35.000 Euro/MW-year to 56.000 Euro/Mw-year, depending on the power production of the units.[22]

3.3.2 Ireland

Ireland introduced a capacity payment scheme in 2003. The main idea was to ensure the security of electricity supply in view of the expected increase of the electricity demand, taking into account the limitations of the interconnections of the country. According to this scheme, the investors that undertake the construction of new plans receive capacity payments based on their capacity availability.

In 2007, the Single Electricity Market (SEM) was launched. The SEM is the wholesale electricity market operating in the Republic of Ireland and Northern Ireland. The SEM introduced an explicit capacity payment mechanism to encourage provision of adequate capacity. Each year, a total capacity payment called the Annual Capacity Payment Sum (ACPS) is calculated by the regulator and it is made available to generators. The total ACPS consists of: (i) the annual cost per kW of a best new entrant peaking generator and (ii) a measure of the total kW of capacity required to meet generation security standard. Remuneration to generators is ca. 75.000-80.000 Euro/MW-year.

It is important to note here also that the capacity mechanism of Ireland does not specify that RES units can also participate in the market.

3.3.3 U.K.

The UK was the first country in Europe to start a capacity auctions market. The first auction for the capacity of 2018/2019 performed in December 2014. The idea was to ensure that there will be enough generators connected to the power network to meet peak (winter) demand. The results of the first capacity market auction were released in December 2015. The auction resulted in a price of £19.4/kW of power capacity. The winners of the auction will sign contracts to provide specific amount of power at 4 hours’ notice (for at least 4 hours) to the national transmission system operator.[22]

For a capacity credit mechanism, the payment that the capacity market ended was the lowest of the ones mentioned above. This price resulted to not attracting power producers with state of the art units to the capacity load, in which the majority of old gas units were implemented back to producing it.

It is important to note at this moment the capacity market in the UK enables only conventional fuel powered units to participate in the auction. The main reason behind this decision is that RES units in the UK are mainly wind farms, which have lot of power production volatility and cannot provide stable power production, if they don't operate alongside with storage. But if there are RES units that can provide stable production in a 4-hour notice then they can also take part in this auction.

4 Power production volatility and the 'duck curve' effect

Increasing energy demand along with the negative impact of fossil energy consumption on climate change impacts, have led to a worldwide boom of renewable energies, especially the technologies based on solar and wind power. However, relying on renewable energy to meet increasing energy demand is still problematic. One of the main concerns of renewable energy production is its volatility due to stochastic weather conditions. Even CSP units, whose production is based on thermal energy, are affected by weather conditions, especially solar dish technology, focused in this thesis. Rapid changes in weather conditions throughout a day can disrupt the operation of a CSP plant, causing the output power production to be volatile. All solar-based powered technologies, including all CSP units, produce electricity as long as the sun has not set. After the sunset, the production of these types of units becomes zero. The occurring situation is that power grids have their peak loads around mid-afternoon hours and at the time of sunset or later, where the sun radiation is low or nonexistent. So there lies a large gap between the peak load and the power production, which needs to be covered for a duration of around 1-2 hours by the conventional power units installed in the power grid. This, in turn, causes a serious problem to the power grid operators, who are committing power units featuring expensive operation or load shedding in some areas of the power grid. Another concerning matter, regarding solar-based power production is, as it is called the 'duck curve' effect.

In this Chapter, these two problematic situations: (a) RES based production, and (b) power grid operators stress is going to be discussed, and how they can be avoided. In Chapter 5, a solution to both these situations is presented by showcasing the operation of a solar dish CSP combined with battery energy storage.

4.1 Power production volatility

As mentioned above, the power production of RES units is driven by the weather conditions. The ideal conditions for RES power production is the weather conditions to remain as smooth as possible, without rapid changes. That is also the best case for CSP power plants, despite operating in thermal cycles, like conventional power plants. CSPs, as mentioned before, use the solar thermal energy to drive a generator to produce electricity. The power output of a CSP is solely depending on the solar thermal power, which is determined by Direct Normal Irradiation (DNI). When the sun power is not enough, or the sky is clouded, or there is a rapid weather change from sunshine to cloudiness, the operation of a CSP is disrupted, as shown in paragraph 5.1. This disruption causes the CSP to suffer large power volatility, which means high power production output fluctuation between two consecutive hours.[23]

To better understand the power production volatility, it is important to examine the DNI received by a CSP and how stable it is. In Figure 10 the typical DNI that reaches the surface of the earth in a summer day in Chania Crete Greece is displayed, while in Figure 11 the DNI of a winter day in the same location is displayed.[23]

From the figures it is clear that DNI, which is the input in a CSP power plant, is not always as stable as required, sometimes with large differences from an hour to the next, as well as the peak-to-peak difference that can occur within a day. The power production volatility causes problems to all concerning parties, especially the owner/producer and the power grid operator. In Table 12 the maximum differences that can occur per season are displayed.

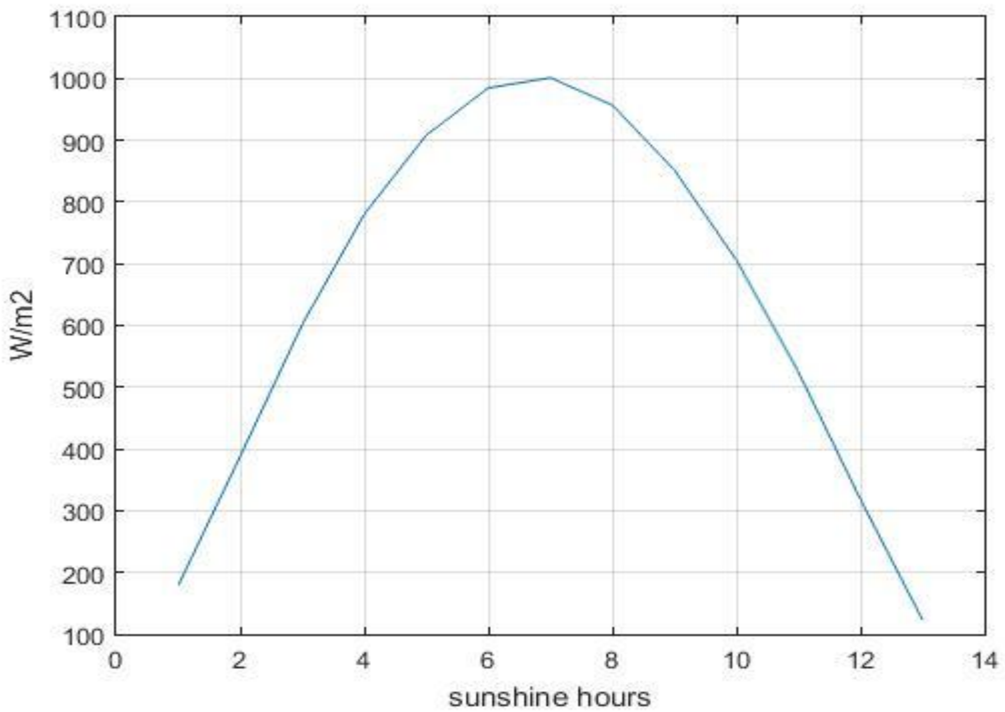

Figure 10: DNI of a summer day

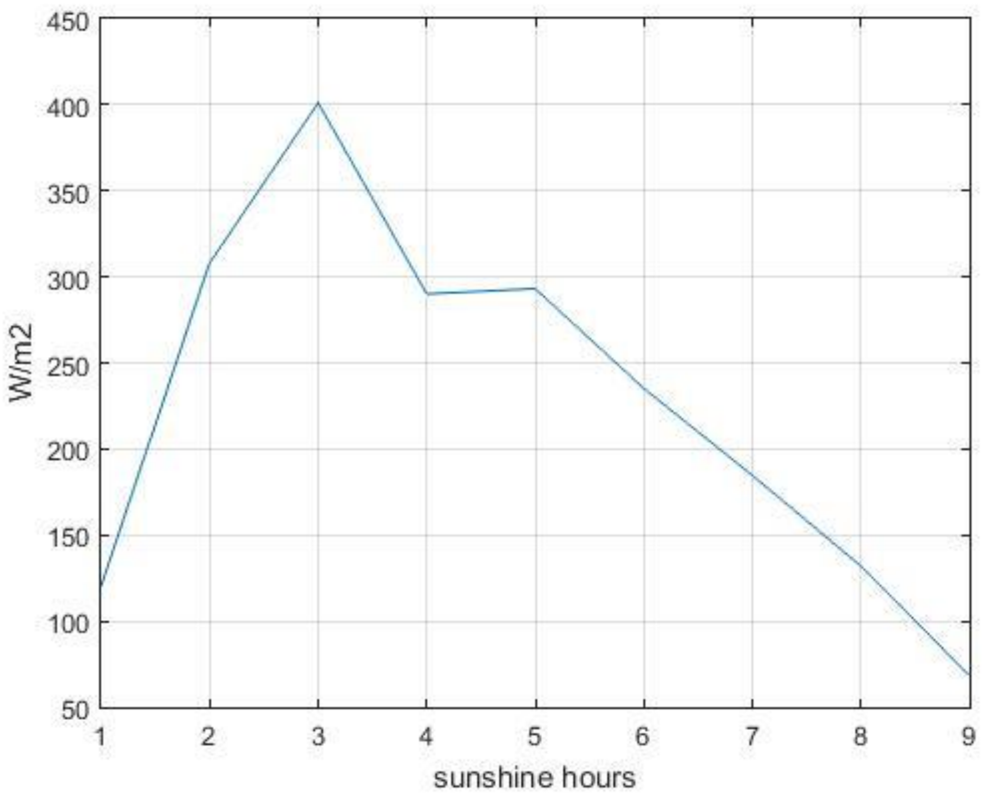

Figure 11: DNI of a winter day

Table 12: Differences that can occur per season

Season	Max peak-to-peak difference (W/m^2)	Max hour-to-hour difference (W/m^2)	Average hour-to-hour difference (W/m^2)
Winter	593	526	193
Spring	753	592	352
Summer	759	689	364
Autumn	660	428	125

Regarding owners or operators of CSP power plants, their main concern is the financial part. In countries where capacity credit remuneration is offered, like Greece, the profit reduction is more evident. Furthermore, fluctuations of DNI can cause a CSP unit to lose the required thermal power to feed the generator installed, resulting in production loss for some hours in a day. This power production disruption is determinant for not reaching capacity credit factors of a CSP power plant.

Power grid operators are responsible for balancing the supply and demand in the power grid. In order to do so, they must have a production schedule for all the units that are providing power to the grid. As for RES units, many power grid operators around the world, as in Greece as well, are obligated to give priority to RES units for the production schedule. RES power production volatility raises insecurity on whether the load demand of the grid is going to be produced at the time needed. If RES units are not able to produce as scheduled, power grid operators have to take a series of actions, in order to supplement the lost power, including engaging units that have quicker response time but much more expensive operation, such as gas turbines.

4.2 The ‘duck curve’ effect

In commercial-scale electricity generation, the duck curve is a graph of power production over the course of a day that shows the timing imbalance between peak demand and renewable energy production. In many energy markets, the peak demand occurs after, or around sunset, when solar power is no longer available. In locations where a substantial amount of solar electric capacity has been installed, the amount of power that must be generated from sources other than solar or wind follow a rapid increase around sunset and peaks in the mid-evening hours, represented by a graph that resembles the silhouette of a duck. In Figure 12 the California duck chart is presented in order to visualize this phenomenon.[24]

The ‘duck curve’ effects can appear due to two main reasons. The first reason is a rapid weather change that can decrease the production of PVs and CSP near zero very quickly. Then the power grid operator must proceed to actions satisfying the current load demand, like committing conventional fuel powered generators. If the time margin is small enough and there is no possible way to commit new generators or increase the production of already committed generators, because of their technical ramp-up limits, then there has to be load shedding to certain areas, in order to preserve the integrity of the grid. [25]

The second reason is that the peak load demand of the power grid appears at the afternoon/evening hours of the day, during which the solar production is low to minimal. This situation also forces the power grid operator to figure out the energy mix needed in order to meet the grid load. If the load is high enough and generators need to be turned on, then the time margin must be within an hour since this effect took place, or else power drops are imminent. [25]

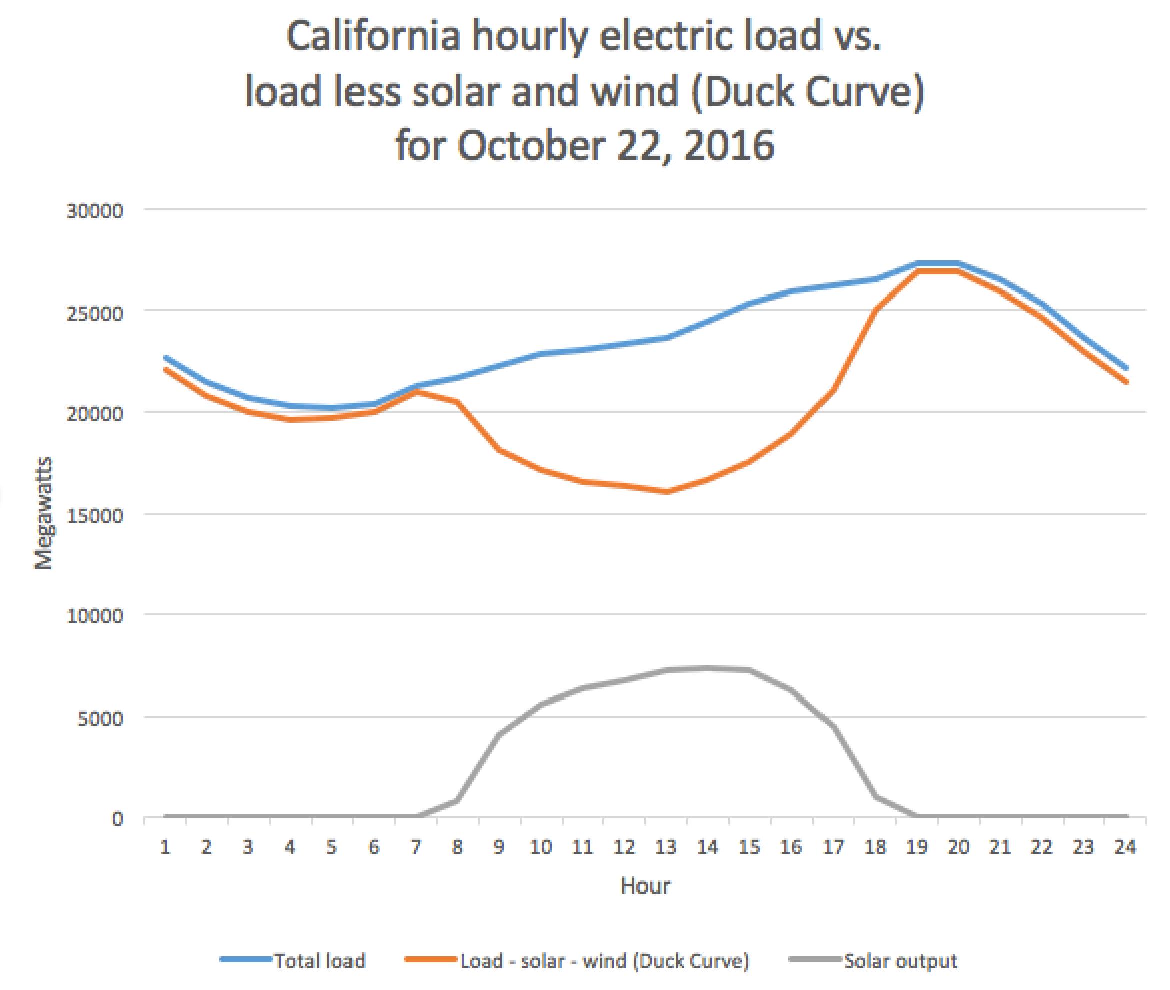

Figure 12: California ISO duck chart [26]

The 'duck curve effect' can also occur in power grids that have lower installed capacity than the one in California, but the solar power production is a large percentage of the overall production of the grid. A grid with these characteristics is the Cretan one, which is the case study power grid of this thesis. Like the Californian one, the Cretan power grid also experiences the 'duck curve' effect. In Figure 13 the average load of the Cretan power grid is displayed. In Figure 14 the load of the Cretan power grid in a summer day, that the demand is increased due to tourism, is displayed. Even when the solar radiation is at its highest the 'duck curve' effect is not reduced.

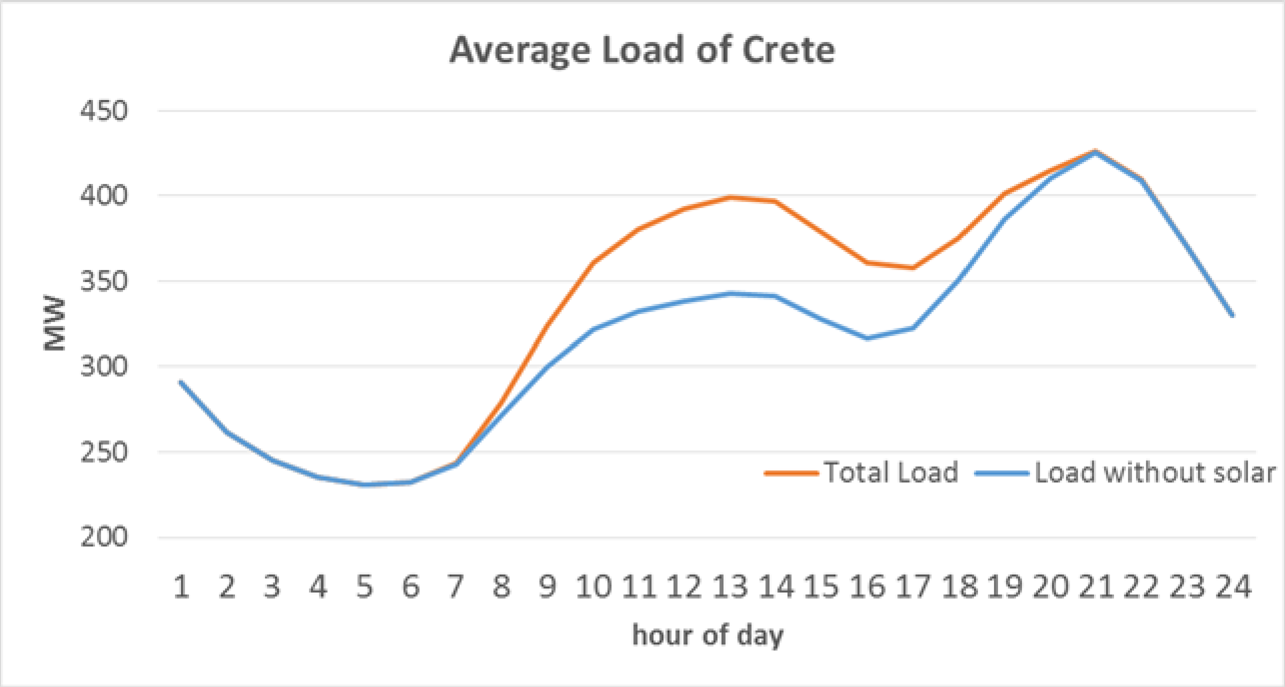

Figure 13: Average load of Cretan power grid

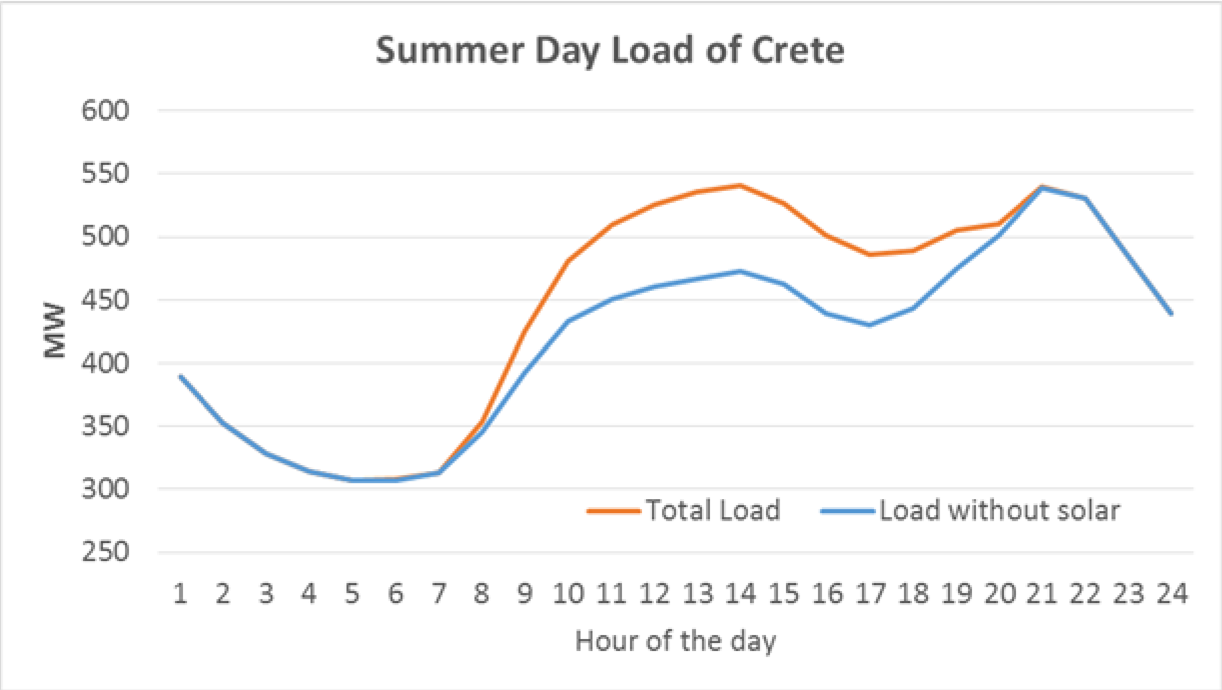

Figure 14: Summer day load of Cretan power grid

It is also important to understand the effect of the 'duck curve' to figure out what time of the day the most changes in demand occur. If the demand is higher in periods that the solar radiation is enough to provide production to cover the demand, then the power grid operator faces a lot of challenges as mentioned before. The times of the day that the most changes in demand occur are displayed, in Figure *15*.

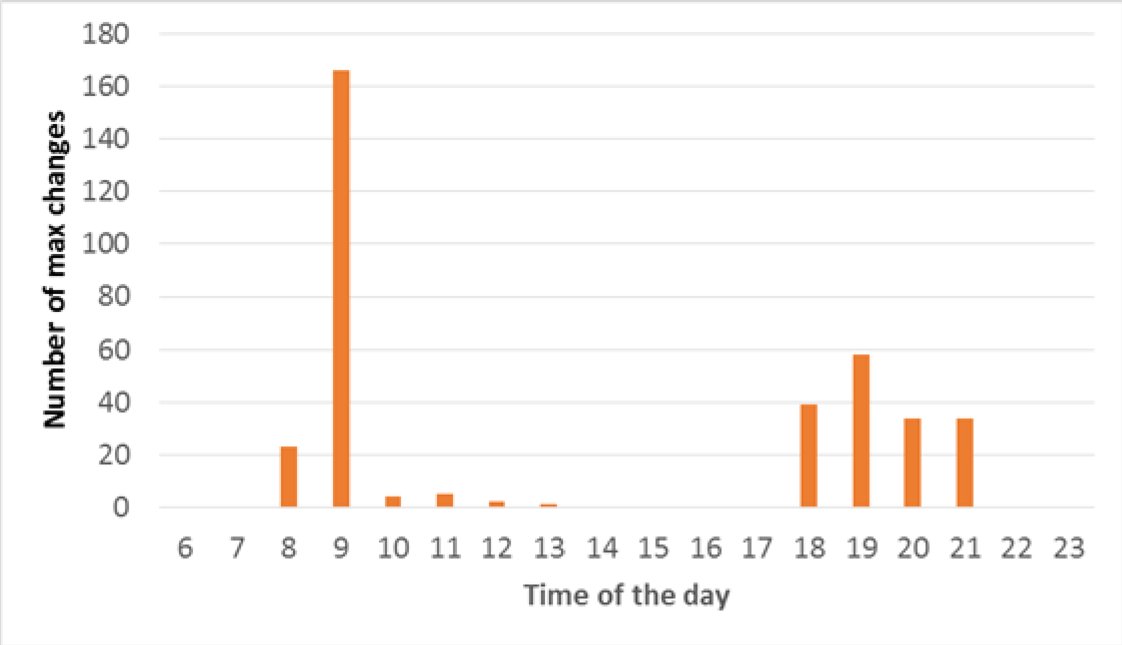

Figure 15: Time of the day in Cretan power grid with the most increases in demand

Except 9:00 where most often increase of demand occurs, the afternoon hours between 18:00 and 21:00 are the most likely for demand to increase. These are the hours of the day when the solar radiation declines or is nonexistent, so the 'duck curve' effect appears and has the effect mentioned above. It is also important, except of the hours that the most changes in load occur, to know the amount of that change, in order to determine the effect that the 'duck curve' has on the power grid. These amounts are displayed in Figure 16.

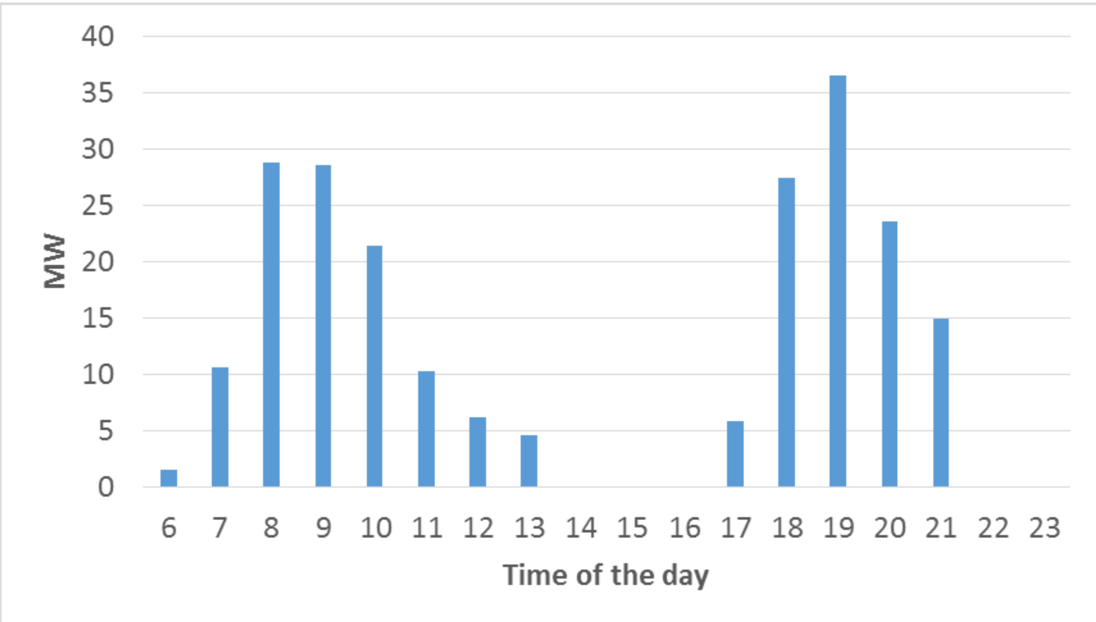

Figure 16: Average load increase of thermal units per hour of the day

4.3 Proposed solutions

The Power production volatility and the 'duck curve' effect are the two most prominent problems that RES units, and CSPs, face. Due to those phenomena, the power grid operators cannot be sure about the production of RES units that lead to a certain level of uncertainty, and how to cover the power grid's load. Despite these facts, there are ways to anticipate the lower power production from RES units or handle it.[24]

The power grid operators, in order to determine the power grid production schedule, use demand production forecast models. [27] These models help them determine which units can produce what amount of power at a given time. But regarding RES units, the situation is a bit more complicated. In order to forecast their production, weather forecast is needed. Weather forecasts are not always 100% accurate, making near impossible to forecast a RES unit production perfectly. In order to add information to the RES models the historic data of weather are also added, which are used in the weather forecast models, in an attempt to predict the weather conditions as optimally as possible. [28]

Another solution to such problems is the utilization of energy storage. Especially for CSPs thermal or battery storage, depending the type of CSP, can be easily utilized to enhance the power production of the power plant. [29] The available storage can be used for power production stabilization, which can solve the power production volatility problem, or the extension of operational hours, which can solve the 'duck curve' problem, or both. The producer can elaborate an operation algorithm, which determines whether or not to utilize the energy storage, or the conventional unit power production he may activate, depending of if he aims to reach the capacity credit factor or to participate in covering the peak load demand and which one is going to produce more profit. [30]

In order to have the best results possible, CSP producers can use both of the methods mentioned above. In order to do so, first the producer must have an accurate behavior model of the CSP power plant. This model can also contain operational algorithms that manipulate the energy storage in order to stabilize and extend the CSP's power production. Then he can provide the power grid operator with a production schedule as accurate as possible. A model with these attributes is presented in Chapter 5.

5 Reduction of Production volatility and 'duck curve' by utilizing lithium-ion batteries in a solar dish CSP

As was mentioned in Chapter 4, the main problems for CSP units' integration into power system are the power production volatility and the 'duck curve' effect. Both of these effects can be handled with the utilization of energy storage alongside the CSP power plant, as well as power production forecasting.

In this thesis, an operating mode of a Hybrid Battery-Stirling Solar dish plant, reducing the volatility of the Stirling Solar Dish output and the 'duck curve' effect, is suggested. The hybrid solar plant consists of a lithium-ion battery bank installed alongside the park, or sharing the same grid. When the solar park produces excessive power, the surplus electricity is stored in the battery bank. The battery energy is used to level potential losses of power production of the plant at another time, or to extend the operational hours of the CSP.

Solar dish CSP is chosen because solar dishes have relatively low power production, as their maximum production reaches about 25 kW, but they can be easily combined together to form a solar thermal park. Such ability allows CSPs consisting of Solar-Dishes to be actually considered as Distributed Generation Units, compared to the rest CSP technologies developed so far. Therefore, this kind of parks can be installed also in non-interconnected power systems, like the Cretan power grid that is showcased in this thesis.

As mentioned before, the core of reducing power production volatility as well as the ‘duck curve’ effect is to develop a model that can provide a power production forecast depending on weather data. In order to obtain a power production forecast a mathematic model, which describes the behavior of the solar dishes, the battery bank must be taken into account too.

5.1 Modelling of solar dish with Stirling Engine

The solar thermal park modeled is of 1 MW nominal power output. The park consists of 40 solar dish-Stirling CSPs of 25 kW nominal capacity each. To simplify modeling, these disks are assumed of the same operation principle. Therefore, after modeling one solar dish-Stirling CSP, the power production prediction is multiplied by 40, in order to obtain the total power production of the park.

The modelling of the solar dish-Stirling system is implemented in three stages, considering each stage connected to the next one and so on. The first stage is the parabolic collector, the next one is the thermal receiver and the last one is the Stirling engine. The solar dishes are placed inside the solar thermal park as shown in Figure 17.

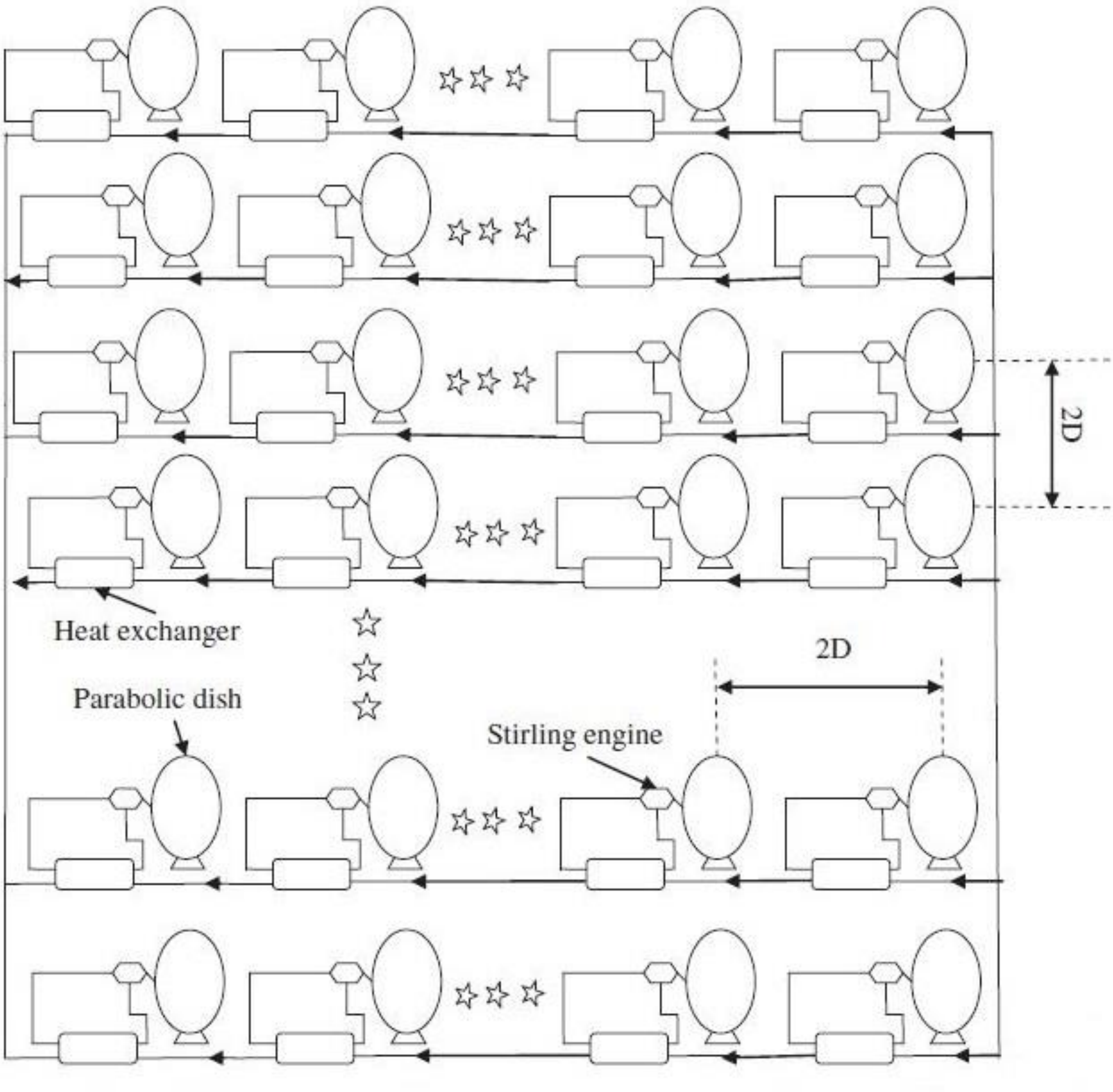

Figure 17: Placement of solar dishes in solar dish CSP

5.1.1 The Parabolic collector

In order to compute the energy from the sun received by the parabolic collector, which afterwards is converted into electricity, the following solar geometry parameters must be calculated: [31]

δ – declination angle

$$\delta = 23.45 \cdot \sin\left(360 \cdot \frac{284+n}{365}\right) \tag{1}$$

where n represents the current day of the year. For example, January 1st is the first day of the year, while February 1st is the 32nd day of the year and so on.

E – Time parameter

This parameter determines the impact the solar radiation throughout the year. It is calculated by equation (2):

$$\begin{aligned} E = {} & 229.199 \cdot \left(0.00075 + 0.001868 \cdot \cos(B) - 0.032077\right) \cdot \sin(B) - \\ & 0.014615 \cdot \cos(2 \cdot B) - 0.04089 \cdot \sin(2 \cdot B) \end{aligned} \tag{2}$$

where:

$$B = (n-1) \cdot \frac{360}{365} \tag{3}$$

and n is the current day of the year.

Solar time

The Solar Time parameter is used to determine the time during which a location receives sunshine, depending on the position of the sun on the sky. The Solar Time is calculated by equation (4):

$$SolarTime = Time + \frac{L_{st} - L_{loc}}{15} + \frac{E}{60} \tag{4}$$

where:

$Time$ - is the time of the day

L_{st} - is the longitude of the location

L_{loc} - the equatorial reference

E - is the Time parameter (see above)

ω – relative solar time

This parameter expresses the time from the solar perspective and is calculated by equation (5):

$$\omega = \left(SolarTime + 12\right) \cdot 15 \qquad (5)$$

where SolarTime is the parameter derived by equation (4).

θz - azimuth angle

The azimuth angle is the angle between the solar rays and the horizontal ground and it's calculated in equation (6):

$$\cos\theta_z = \sin\phi \cdot \sin\delta + \sin\phi \cdot \sin\delta \cdot \cos\omega \qquad (6)$$

where:

φ - is the latitude of the location

δ - is the declination angle derived from equation (1)

ω - is the relative solar time derived from equation (5)

θ – collector angle

This parameter describes the angle between the solar rays and the leveled parabolic collector and is calculated by equation (7):

$$\begin{aligned} \cos\theta = {} & \sin\delta \cdot \sin\phi \cdot \cos\beta - \sin\delta \cdot \cos\phi \cdot \sin\beta \cdot \cos\theta_z + \\ & \cos\delta \cdot \cos\phi \cdot \cos\beta \cdot \cos\omega + \cos\delta \cdot \sin\phi \cdot \sin\beta \cdot \cos\theta_z \cdot \cos\omega + \\ & \cos\delta \cdot \sin\beta \cdot \sin\theta_z \cdot \sin\omega \end{aligned} \qquad (7)$$

After the calculation of all the solar parameters, the solar radiation concentrated on the parabolic collector is calculated by equation (8):

$$Q_a = I_b \cdot A_g \cdot \cos\theta \cdot \gamma_r \cdot IF \cdot n_d \qquad (8)$$

where:

Q_a - is the concentrated solar radiation

I_b - is the direct solar radiation

A_g - is the collector surface

$\cos\theta$ - is the collector angle (if the solar dish has a azimuth tracking system then $\cos\theta = 1$)

γ_r - is the collector reflectivity $(\gamma_r = 0.92)$

IF - is the reflectivity parameter $(IF = 0.92)$

n_d - are the loses due to dust $(nd = 0.98)$

The solar radiation concentrated by the parabolic collector of a solar dish CSP is calculated employing equation (8). This amount of energy is forwarded to the thermal receiver in order to be transformed to thermal energy. [33]

5.1.2 The Thermal Receiver

The thermal receiver of a solar dish-Stirling CSP is located to the focal point of the parabolic collector and collects the thermal energy of the solar rays. The total energy output of the thermal receiver is reduced by the energy losses. These losses are divided in two categories: losses due to energy transformation and radiation losses.[32] [34]

Losses due to energy transformation are calculated by equation (9):

$$Q_{conv} = h_{total} \cdot A_{cav} \cdot (T_{cav} - T_a) \tag{9}$$

where:

A_{cav} - is the receiver surface

T_{cav} - is the receiver temperature

T_a - is the environment temperature

The total thermal energy transfer constant h_{total} is calculated by:

$$h_{total} = h_{natural} + h_{forced} \tag{10}$$

where:

$h_{natural}$ - is the natural thermal energy transfer constant

h_{forced} - is the forced thermal energy transfer constant

The $h_{natural}$ parameter depends on the area the solar park is and the local temperature, where h_{forced} depends on the wind velocity and is calculated by equation (11):

$$h_{forced} = 0.1967 \cdot V_w^{1.849} \tag{11}$$

where V_w is the wind velocity.

The radiation losses are split in two subcategories: losses due to reflectivity and losses due to emission. The losses due to reflectivity are calculated by equation (12):

$$Q_{rad\,\mathrm{Refl}} = \left(1 - a_{eff}\right) \cdot Q_a \qquad (12)$$

where:

a_{eff} - is the receiver radiation absorptivity

Q_a - is the energy collected in parabolic collector

The losses due to emission are calculated by equation (13).

$$Q_{radEmit} = \varepsilon_{eff} \cdot A_{cav} \cdot \left(T_{cav}^4 - T_a^4\right) \qquad (13)$$

where:

ε_{eff} - is the receiver absorptivity factor $(= 0.98)$

A_{cav} - is the receiver surface

T_{cav} - is the receiver temperature

T_a - is the environment temperature

The total losses, regarding the thermal receiver, are calculated by equation (14):

$$Q_{loss} = Q_{conv} + Q_{rad} \qquad (14)$$

The total energy output of the thermal receiver, which is directed to the Stirling engine, is calculated by equation (15):

$$Q_u = Q_a - Q_{loss} \qquad (15)$$

5.1.3 The Stirling engine

The Stirling engine, which is connected to the thermal receiver directly, receives the energy from the thermal receiver calculated in equation (15). Due to the high complexity of thermodynamic modelling, the efficiency of the Stirling engine is not modelled but approximated to 38%, which is an average value for such an engine. [32] The total power produced by the Stirling engine is calculated by equation (16):

$$W = n_{load} \cdot Q_u \cdot n_{al} \tag{16}$$

where:

n_{load} - is the Stirling engine efficiency (=0.38)

Q_u - is the energy input to the engine

n_{al} - is the efficiency of the converter (=0.98)

All the above equations assure power production prediction of the solar thermal park for every hour of the year. In

Table *13*, all the parameters used, which do not depend on the inputs of the system, along with their values, are listed.

5.2 Modelling of the battery bank

In order to reduce power production volatility or the ‘duck curve’ effect of the park, installation of a battery bank is proposed. It is important to note that the battery bank in not necessarily installed within the solar thermal park, but they combination acts as one controlled entity. The main goal for this power exchange is to reduce production volatility and achieve production level closer to the average production of the solar thermal park or the extension of the operational hours of the power plant.

The battery bank consists of lithium-ion batteries of the Sanyo DCB-102 type, whose characteristics are shown in

Table 13: Constant parameters and their values

Symbol	**Value**
Focal length L	7.45 (m)
Collector surface Ag	87.67 (m2)
Mirror reflectivity γr	0.92
Absorptivity factor IF	0.92
dust losses factor nd	0.98
cavity diameter Acav	0.45 (mm)
Cavity absorptivity acav	0.96
cavity emissivity eeff	0.9
longitude Lloc	24.018 (^{o})
equatorial reference Lst	30 (^{o})
latitude F	35.51
receiver surface Aca	0.2 (m2)
Stirling engine efficiency nload	0.385
Boltzmann constant s	5.67*10-8
converter efficiency nal	0.98

Table 14. [35] [36]

Table 13: Constant parameters and their values

Symbol	**Value**
Focal length L	7.45 (m)
Collector surface Ag	87.67 (m^2)
Mirror reflectivity γ_r	0.92
Absorptivity factor IF	0.92
dust losses factor n_d	0.98
cavity diameter A_{cav}	0.45 (mm)
Cavity absorptivity a_{cav}	0.96
cavity emissivity e_{eff}	0.9
longitude L_{loc}	24.018 (°)
equatorial reference L_{st}	30 (°)
latitude F	35.51
receiver surface A_{ca}	0.2 (m^2)
Stirling engine efficiency n_{load}	0.385
Boltzmann constant s	$5.67*10^{-8}$
converter efficiency n_{al}	0.98

Table 14: Sanyo DCB-102 characteristics

Symbols	**Value**
battery capacity C_{bat}	1.59 kWh
maximum discharge power $P_{max-dis}$	-340 W
maximum charge power P_{max-ch}	720 W
nominal voltage V_{dc}	48 V
price	1000 €/kWh
Inverter price	150 €/kW

The battery bank may have only three states, operating only in one of them at any specific time. [36] These states are:

(a) The charging state,

(b) The discharging state and,

(c) The idle state.

When the battery is being charged, its operation is described by equations (17)-(19):

$$I_{bat}(t) = \min\left(I_{\max}, \frac{SOC_{\max} - SOC(t-1)\cdot\frac{C_{bat}}{U_{dc}}}{dt}, \frac{P_{load}(t)\cdot n_{acdc}}{U_{dc}}, \frac{P_{bidi}}{U_{dc}} \right) \tag{17}$$

$$P_{bat\_ch} = I_{bat}(t)\cdot U_{dc} \tag{18}$$

$$SOC(t) = SOC(t-dt) + \frac{I_{bat}(t)\cdot dt\cdot n_{bat\_ch}}{C_{bat}/U_{dc}} \tag{19}$$

where:

I_{bat} – charge current of battery

P_{bat_ch} – charge power of battery

I_{max} – maximum charge current (produced by Pmax-ch)

SOC – State Of Charge

C_{bat} – battery capacity

U_{dc} – DC channel voltage

n_{acdc} – ac-dc conversion efficiency

P_{bidi} – bi-directional converter efficiency

n_{bat_ch} – charge of battery efficiency

dt – time frame between two calculations (=1 h)

When the battery is being discharged, its operation is described by equations (20)-(22):

$$I_{bat}(t) = \min\left(I_{\max}, \frac{\left(SOC(t-1) - SOC_{\min}\right)\cdot\frac{C_{bat}}{U_{dc}}}{dt}, \frac{P_{load}(t)}{U_{dc}\cdot n_{dcac}}, \frac{P_{bidi}}{U_{dc}\cdot n_{dcac}} \right) \tag{20}$$

$$P_{bat\_dis} = I_{bat}(t)\cdot U_{dc} \tag{21}$$

$$SOC(t) = SOC(t-dt) - \frac{I_{bat}(t) \cdot dt \cdot n_{bat\_dis}}{C_{bat} / U_{dc}} \quad (22)$$

where:

P_{bat_dis} - is the discharge power of battery

n_{dcac} - is the dc-ac conversion efficiency

n_{bat_dis} - is the battery discharge efficiency

SOC_{min} - is the lowest charge state of battery

When the battery is not used and is in its idle state, its operation is described by equation (23):

$$SOC(t) = SOC(t-dt) \cdot (1-d) \quad (23)$$

Where d is the self-discharge constant of the battery (=0.005)

The parameters featuring constant values are displayed in Table 15.

Table 15: Parameter values of battery bank

Symbols	**Values**
maximum state of charge SOC_{max}	1
Minimum state of charge SOC_{min}	0.2
ac to dc conversion efficiency $n_{ac\text{-}dc}$	0.97
dc to ac conversion efficiency $n_{dc\text{-}ac}$	0.96
charging efficiency $n_{bat\text{-}ch}$	0.95
discharging efficiency $n_{bat\text{-}dis}$	0.95

5.3 Power production volatility reduction

The behavior and operation of each component of the Hybrid solar thermal park is described in the previous sections. In this section, the proposed algorithm for the schedule of the active power of the hybrid solar dishes and battery bank, aiming to reduce the power production volatility, along with the sizing of the battery bank capacity, is described.

5.3.1 The Algorithm for power production volatility reduction

As a first step towards the optimal operation of the solar park, an algorithm that reduces the production volatility as much as possible is proposed. This algorithm aims towards the optimum management of energy produced by the solar park, to ensure higher capacity credit, which, in turn, can be remunerated according to the Grid codes. [37] To achieve higher efficiency, the algorithm tries to reduce volatility in a day-by-day scenario.

By reducing volatility, the owner of the solar thermal park can gain many benefits, such as more operating hours and confirmed capacity credit, as long as bidding higher during the hours that ensure the highest prices.

The algorithm for reducing power production volatility operates in two steps. In the first step, the algorithm computes the expected mean value of power production for the specific day. If the actual production is higher than the mean value, then the excessive power is used to charge the batteries. If the actual production is lower than the mean value then the batteries' power is used to cover the difference. In the second step, the mean squares error method is used in order to ensure that the volatility reduction converges near optimal. In this stage, the actual production and the production calculated in the first stage are compared and, employing Least Squares Error minimization techniques, the production minimization of the mean square error is calculated. The production derived after the second stage of the algorithm satisfies the technical requirements of both the solar dishes and the battery bank, as well as their efficiency and is the best production volatility reduction that can be achieved.

The formulas that the algorithm operates on are shown in equations 24-32.

$$Mean_{pp} = mean\left(\mathrm{Re}\,al_{pp}\right)\cdot n \tag{24}$$

$$\begin{aligned}
&\mathrm{Re}\,al_{pp} > Mean_{pp}\\
&state = 1\left(ch\arg e\right)\\
&\mathrm{Re}\,al_{pp} < Mean_{pp}\\
&state = 0\left(disch\arg e\right)\\
&\mathrm{Re}\,al_{pp} = Mean_{pp}\\
&state = -1\left(iddle\right)
\end{aligned} \tag{25}$$

$$\mathrm{Pr}\,oposed_{pp} = mse\left(\mathrm{Re}\,al_{pp}, Mean_{pp}, state\right) \tag{26}$$

$$P_{bat} = \mathrm{Re}\,al_{pp} - \mathrm{Pr}\,oposed_{pp} \tag{27}$$

$$MaxDisch\arg e_{rate} \leq P_{bat} \leq MaxCh\arg e_{rate} \tag{28}$$

$$SOC = SOC_{last} + \frac{Pbat}{Cbat}\cdot n_{bat} \tag{29}$$

$$SOC_{\min} \leq SOC \leq SOC_{\max} \tag{30}$$

$$MaxDisch\arg e_{rate} = \min\left(\left(SOC_{\min} - SOC\right)\cdot \mathrm{Cbat}, \mathrm{MaxDischarge}\right) \tag{31}$$

$$MaxCharge_{rate} = \max\left(\left(SOC_{\max} - SOC\right) \cdot Cbat, MaxCharge\right) \qquad (32)$$

Where:

$Real_{pp}$ - is the real production of the solar dish park without the batteries

$Mean_{pp}$ - is the mean production of the solar dish park

N - is the efficiency of the park

State - is the state of the algorithm regarding the energy transferred to/from the battery bank

$Proposed_{pp}$ - is the proposed operation of the CSP utilizing batteries that minimizes mean square error

P_{bat} - is the power that is exchanges between the park and the battery bank

$MaxDischarge_{rate}$ - is the maximum power the battery bank can provide while discharging at that given time providing there is enough left in the battery (capped by MaxDischarge)

$MaxCharge_{rate}$ - is the maximum power the battery bank can absorb while charging at that given time providing the fact that the battery is not fully loaded (capped by MaxCharge)

SOC - is the State of Charge of the battery bank

C_{bat} - is the battery bank capacity

n_{bat} - is the battery bank efficiency

SOC_{min} - is the minimum SOC

SOC_{max} - is the maximum SOC

$MaxDischarge_{rate}$ and $MaxCharge_{rate}$ are bounded by the technical limits of the battery bank as shown in

Table 13: Constant parameters and their values

Symbol	Value
Focal length L	7.45 (m)
Collector surface Ag	87.67 (m2)
Mirror reflectivity γr	0.92
Absorptivity factor IF	0.92
dust losses factor nd	0.98
cavity diameter Acav	0.45 (mm)
Cavity absorptivity acav	0.96
cavity emissivity eeff	0.9
longitude Lloc	24.018 (^{o})
equatorial reference Lst	30 (^{o})
latitude F	35.51
receiver surface Aca	0.2 (m2)
Stirling engine efficiency nload	0.385
Boltzmann constant s	5.67*10-8
converter efficiency nal	0.98

Table 14, which for the whole battery bank are 320 kW and -151 kW, respectively. These two rates describe the maximum power that the bank can provide or absorb at a given time, according to the state of the bank, as well as the power that is already provided or absorbed by the battery bank.

Equations (24) and (25) determine whether to charge or discharge the batteries, while equation (26) determines the appropriate operation to minimize mean square error of the park. Equations (27) and (28) are about the power that is absorbed or supplied to the battery bank and its minimum and maximum values allowed at a given hour. Equations (31) and (32) refer to determining the limits that the power to battery has per hour. Equations (29) and (30) are the calculation formulas of the SOC of the battery bank and its limits.

It is important to note here that the energy provided to the grid by the park in some days is lower than the power production of the solar dishes. This is expected because some energy is lost in the exchange of energy between the solar dishes and the battery bank, as mentioned in paragraph 5.1.

The flow diagram of the algorithm is shown in Figure 18 .

5.3.2 The Battery bank sizing algorithm

Based on the algorithm described in the previous section, there is a way not only to smoothen the production of the solar dish thermal park but also to elaborate a mechanism assuring that production volatility is reduced and capacity credit can be achieved.

To derive the battery size necessary for the optimal algorithm operation, the maximum difference between the actual and the optimized operation, which can occur within a day, is calculated. This difference dictates the size of the battery bank that is essential for the algorithm operation.

The capacity of the battery bank is the maximum difference in power between the real production and the proposed by the algorithm, within an hour. For the present case study, the maximum difference resulting within an hour is approximately 700 kW. Thus, the battery bank must feature a 700 kWh capacity in order to eliminate this maximum difference. This battery bank can be assembled with various battery strings connections. The goal here is to find the minimum number of batteries that can fulfill the needs of the system, thus ensuring the lower cost. The requirements of the proposed system are not only the power bank capacity and the scheduling fast response, but also the dc to ac converter characteristics.

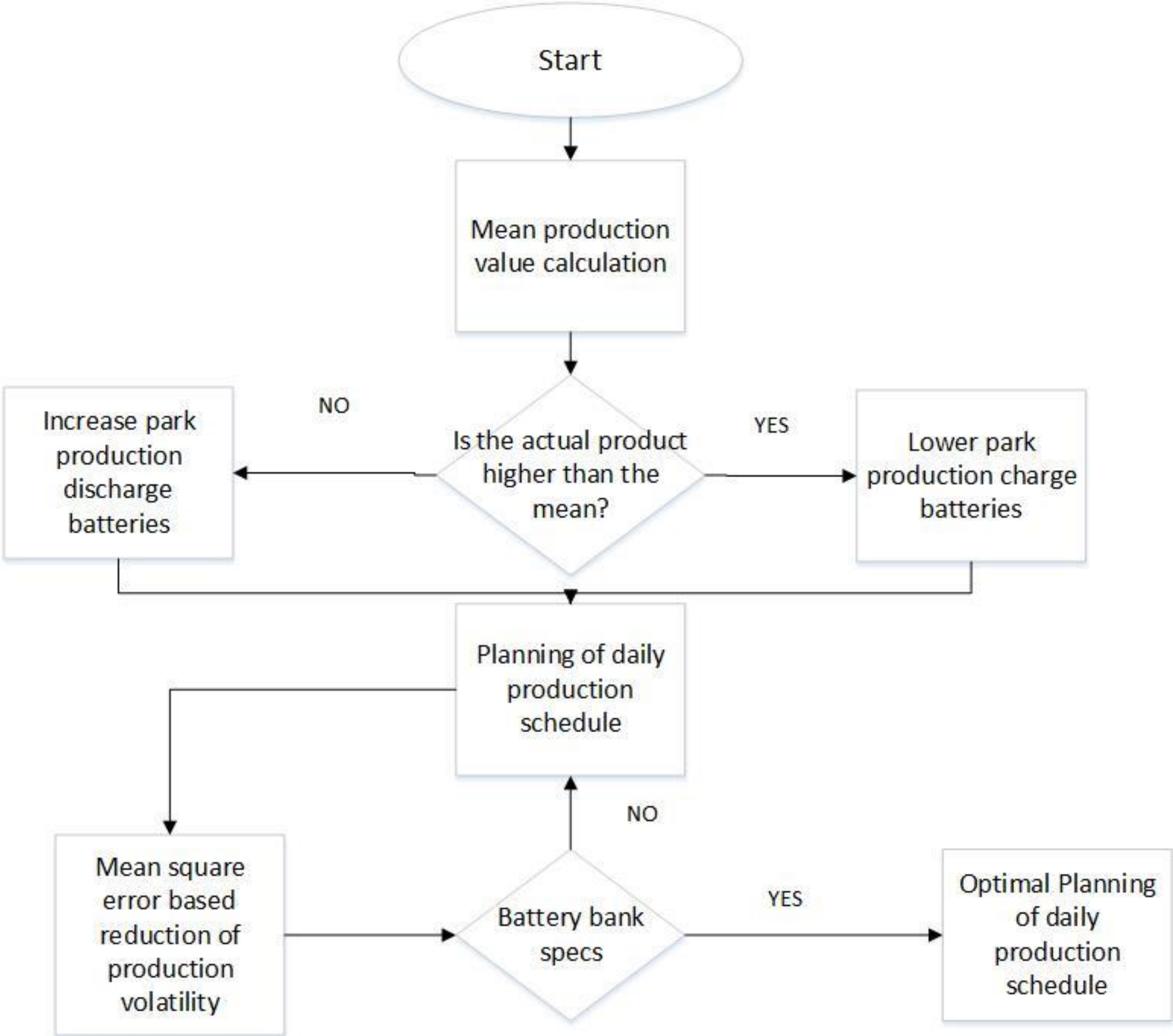

Figure 18: Flow chart of the Algorithm for production volatility reduction.

The bi-direction converter from dc to ac and vice versa, for the present case study, is rated to a power capacity of 700 kW [36] , but its voltage range varies for 480 to 600 V. Regarding the voltage range, there can be 11-13 batteries in a row, as the nominal voltage of one battery is 48 V.

The algorithm operation concept is to check every possible combination of battery topology and discover the least expensive one. Subsequently, taking into consideration the restrictions mentioned above, the economic impact on the solar thermal plant of every possible topology is calculated and the least costly topology is derived. The flow chart of the algorithm is illustrated in Figure 19.

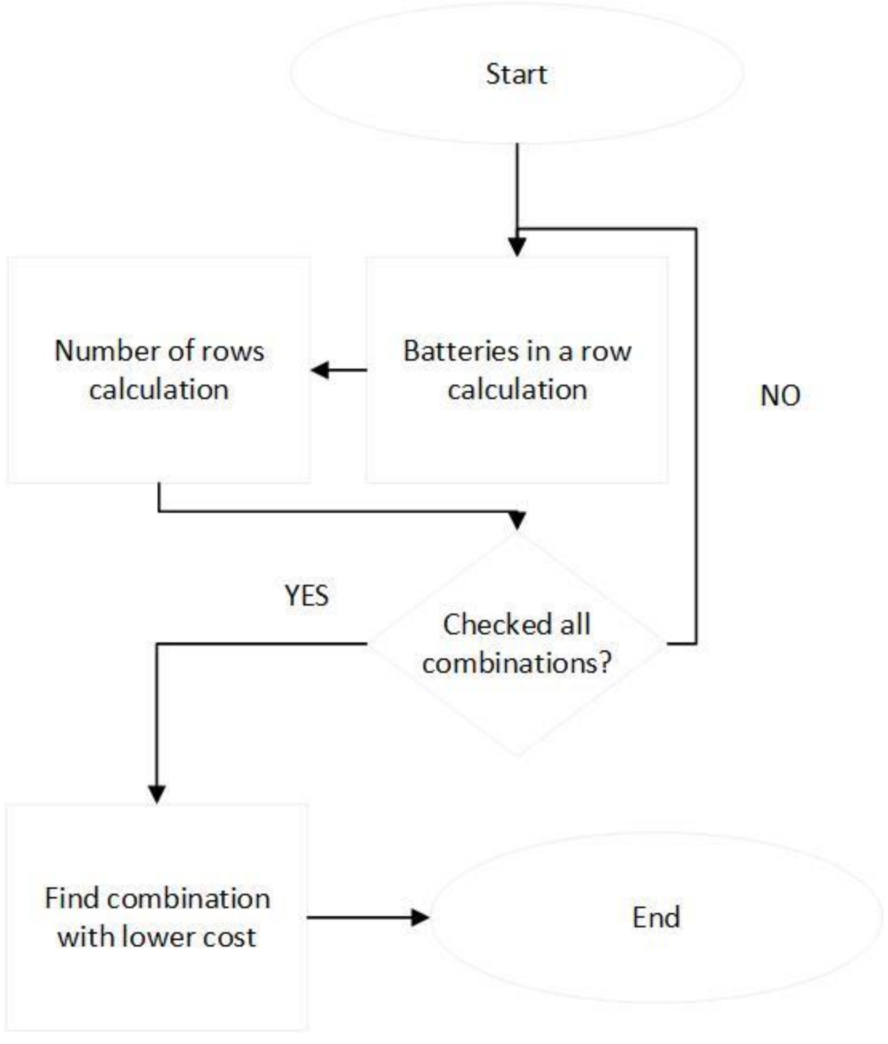

Figure 19: The flow chart of the Battery bank sizing algorithm.

After the evaluation of all possible outcomes, the algorithm suggests for the present case study, the minimum number of batteries to be 12 in a row with 37 rows of them. Except for the consideration to cover 100% of the production difference mentioned above, the considerations to cover 80% and 60% are examined too. For the 80% case, a combination of 12 batteries in a row with 28 rows is required, while for the 60% case, a combination of 11 batteries in a row with 25 rows is required.

5.4 Power production volatility reduction results

In this section, the difference between the output of the Hybrid Solar-Thermal Park and the output of the Solar Thermal Park alone is computed, exploiting the proposed algorithm. Focus is given on the comparison of the output between the “proposed” operation by the algorithm and the expected operation based on actual solar data from the meteorological station at the Technical University of Crete.

The production volatility reduction expectation is that the ‘proposed’ production should give graphs that form much lower peak-to-peak values compared to the ‘real’ ones. In a given time period, it is easier to extract conclusions about how much more efficient is the smoothing of the production. It is important to note here that the smoothing of the production occurs only during the hours of a day with sunshine.

In the following figures, the exchange to/from the battery bank and the hourly limits for charging and discharging the battery are shown for each example. These limits not only take into account the battery characteristics as presented in

Table 13: Constant parameters and their values

Symbol	Value
Focal length L	7.45 (m)
Collector surface Ag	87.67 (m2)
Mirror reflectivity γr	0.92
Absorptivity factor IF	0.92
dust losses factor nd	0.98
cavity diameter Acav	0.45 (mm)
Cavity absorptivity acav	0.96
cavity emissivity eeff	0.9
longitude Lloc	24.018 (^{o})
equatorial reference Lst	30 (^{o})
latitude F	35.51
receiver surface Aca	0.2 (m2)
Stirling engine efficiency nload	0.385
Boltzmann constant s	5.67*10-8
converter efficiency nal	0.98

Table 14, but also the state of charge of the battery as a result of the proposed algorithm, as described previously. These limits can change depending on the SOC of the battery and its technical limits.

Examining characteristic days throughout a year, a typical day for winter was picked that is the first day of the year. As shown in Figure 20, it is obvious that the production stabilization is far more achieved than before and also provides a capacity credit equal to 120 kW. Since the January 1st was one of the lowest production days of the year, the production of a day in December is also presented, with lower cloudiness than 1st of January. In Figure 21, the production volatility reduction, as long as the capacity credit, which is 200 kW, is highly achievable, as long as the volatility reduction is more prominent.

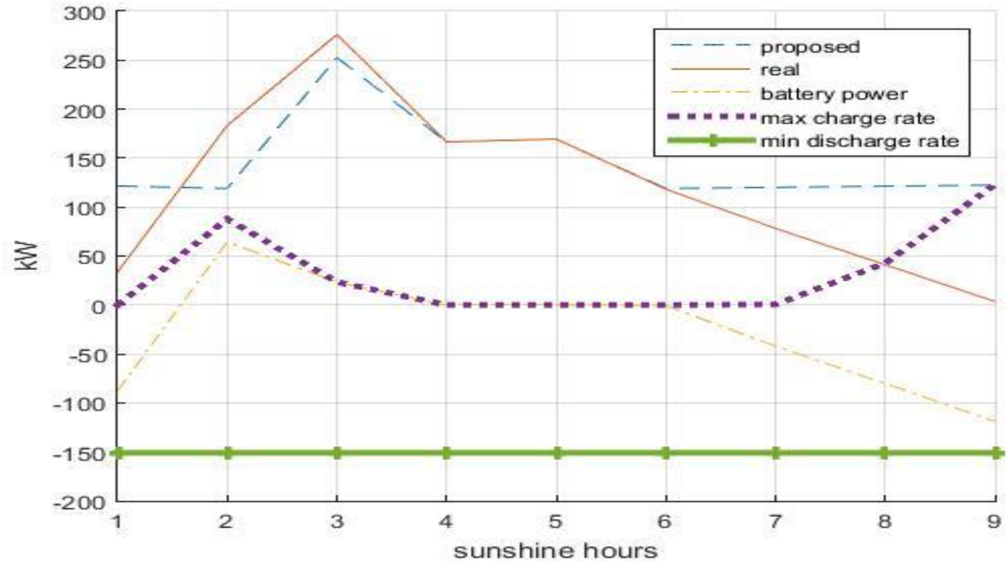

Figure 20: Production comparison for January 1st

Examples for the volatility reduction during a spring day and a summer day are shown in Figure 22 and Figure 23, respectively. In these examples, the capacity credit factor achieved is 200 kW and 250 kW respectively, while after the second hour of sunshine the production is stabilized to 500 kW and 570 kW respectively, before dropping again in the afternoon hours.

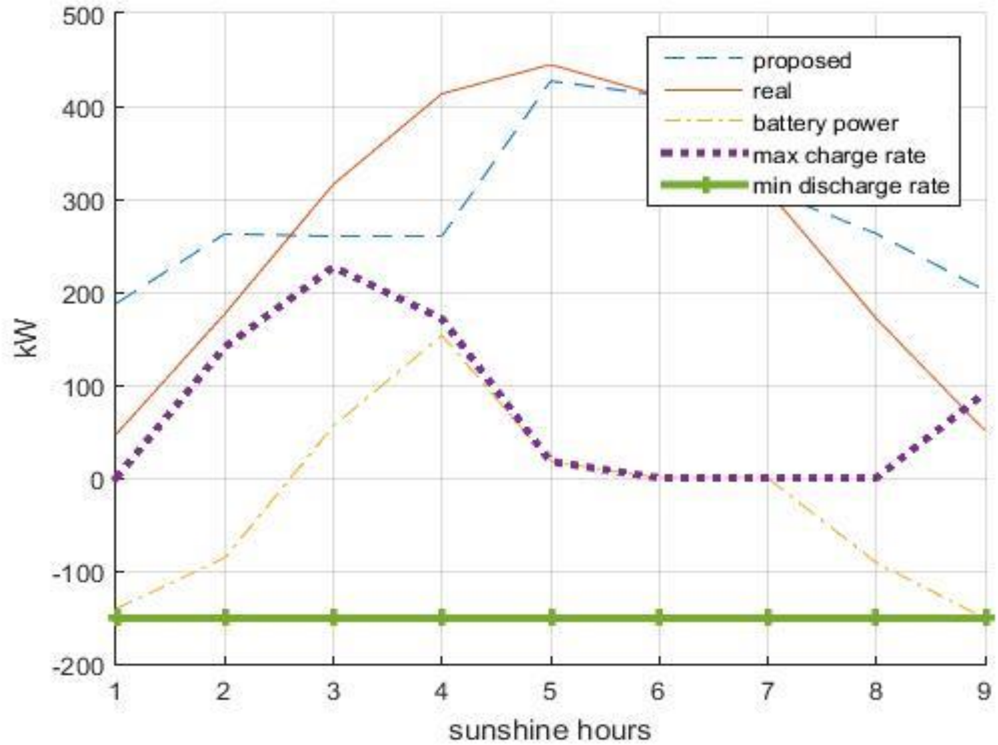

Figure 21: Comparison of production in a typical winter day

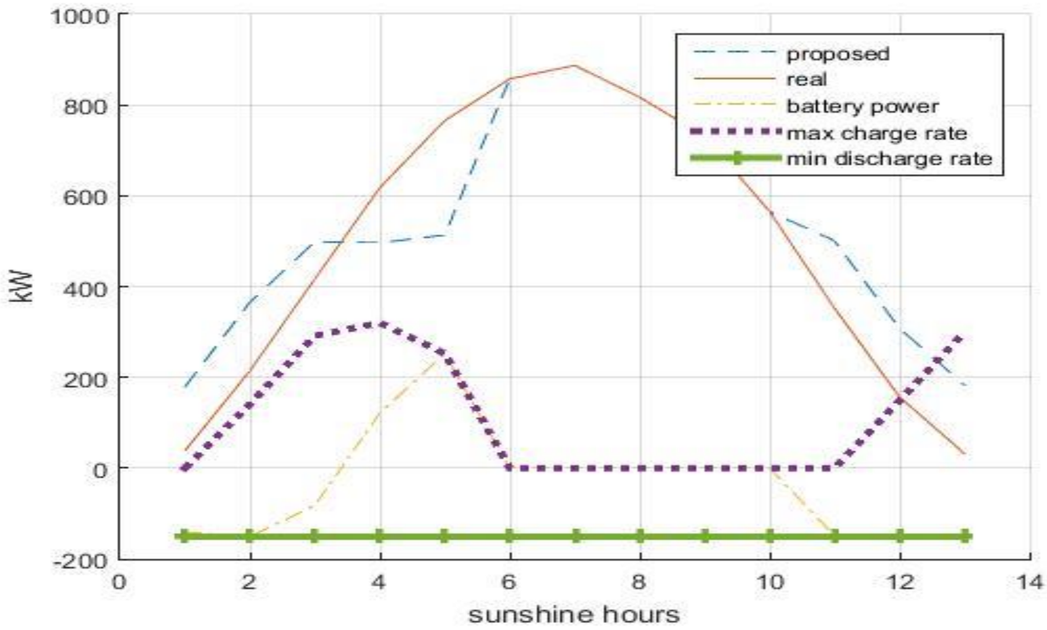

Figure 22: Comparison of production in a typical spring day

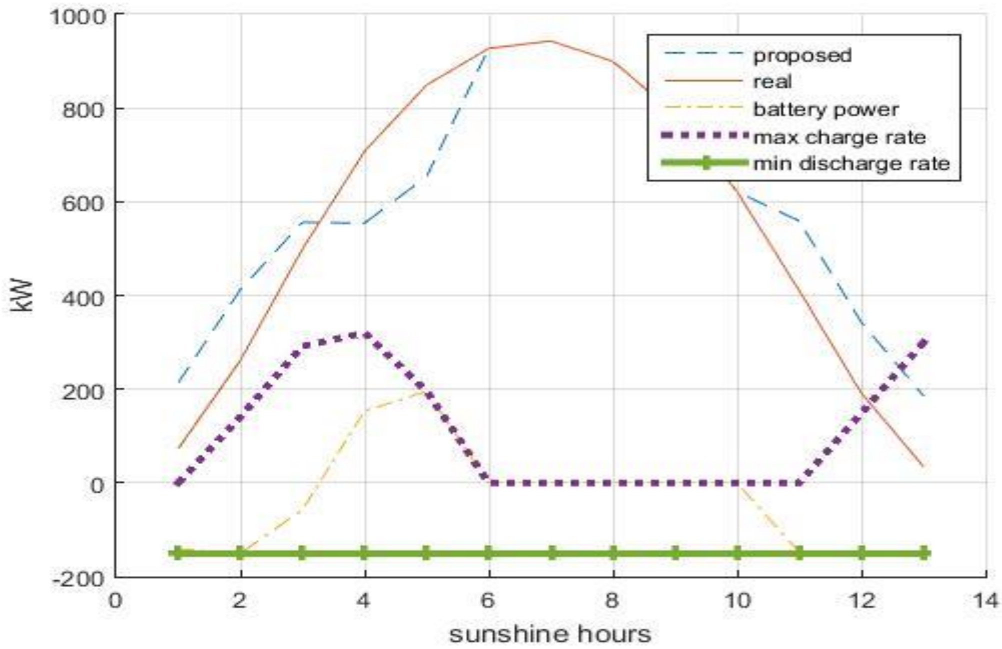

Figure 23: Comparison of production in a typical summer day

Finally, an example of a typical autumn day is illustrated in Figure 24. During autumn, cloudiness varies quicker on Crete, thus affecting considerably the solar radiation output. Even for this high fluctuating output, the algorithms also ensures production stability and capacity credit for the system, which reaches 120 kW.

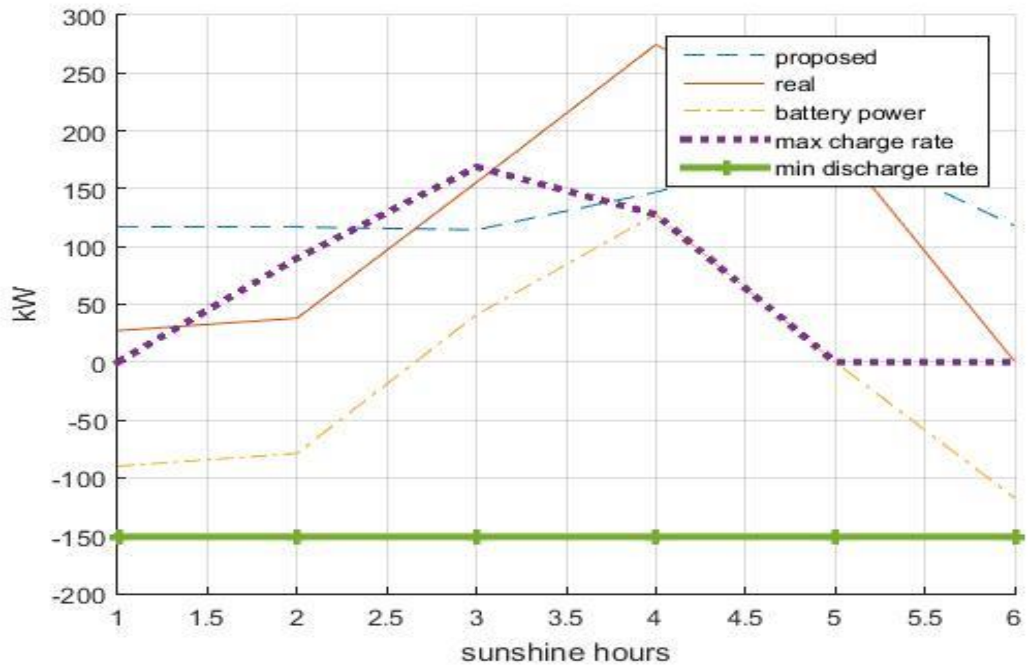

Figure 24: Comparison of production in a typical autumn day.

Apart from the results above, the mean square error (MSE) factor reduction, before and after the algorithm application as described in paragraph 5.3.1, as well as the peak-to-peak reduction factor are important factors too. In Table 16, the average results for each season are listed.

Table 16: MSE result for every season

Season	**MSE reduction (%)**	**Peak to Peak reduction (%)**
Winter	72.7	72.35
Spring	93.9	17.18
Summer	95.62	16.63
Autumn	41.43	72.13

Regarding the examples above, it is concluded that the installation of the batteries reduces the production volatility to a great extent and achieves capacity credit for a day period, even with some loss of energy, while benefits drastically the power grid as a whole. Power production volatility reduction has many advantages for all involved members, from the producers to the operator of the island. First of all, regarding the volatility reduction, decreasing at the same time the uncertainty of such sources, the power grid operators are enabled to include solar dish-Stirling units more easily and frequently in the power production schedule of the grid.

The owner of the Hybrid plant can provide capacity credit to the power system, as shown and described in the figures above, which can be additionally remunerated as referred in the Non-Interconnected Islands Grid Code of Greece. [37]

5.5 The 'duck curve' effect reduction

The behavior and operation of each component of the Hybrid solar thermal park has been described in the previous sections. Also, an algorithm for power production volatility reduction is proposed. In this section, an algorithm is described achieving energy distribution between the solar dishes and the battery bank, aiming to reduce the 'duck curve' effect, which was mentioned in Chapter 4.

5.5.1 The Algorithm for the 'duck curve' effect reduction

In order to reduce the 'duck curve' effect in a power grid, the solar-based RES production must include energy storage, like the solar dish CSP proposed in this section. The purpose of the battery bank is to provide energy at late afternoon hours, when the power production of the CSP is at the lowest, and extend the operational hours of the CSP.

The proposed operation of Hybrid solar thermal park for the reduction of the 'duck curve' effect, is to provide the 15% of the power plants nominal capacity for two hours after the sun is set. The reduction of the 'duck curve' of the CSP, enables the power grid operator to further engage the CSP in the energy production schedule, in order to smoothen the generation transition from solar to conventional fuel.

The algorithm that reduces the 'duck curve' effect operates in two stages. In the first stage the algorithm ensures that for two hours after the sunset the CSP will produce the 15% of its nominal capacity, which is 150 kW, for each hour. In the second stage, the energy that is left on the battery, after subtracting the amount needed to provide power production for two hours after the sunset, is used to provide part power production stabilization, as described in paragraph 5.3.1. The extra parameter that this version takes into account is that by the end of the day there is enough energy in the battery left to run the algorithm for the next day.

The operation of the algorithm is described by the equations (24) to (32) with the addition of the equations (31) and (32) that are extra conditions for the algorithm.

$$\mathrm{Pr}\mathit{oposed}_{pp}\left(end\right)=\mathrm{Proposed}_{pp}\left(end-1\right)=0.15\cdot No\min alCapacity \tag{33}$$

$$SOC_{end}>0.4 \tag{34}$$

Where:

$\mathrm{Proposed}_{pp}$(end) and $\mathrm{Proposed}_{pp}$(end-1) - is the proposed production after the two hours of sunshine

SOC_{end} - is the SOC at the end of the day

The flow chart of the algorithm is presented in Figure 25.

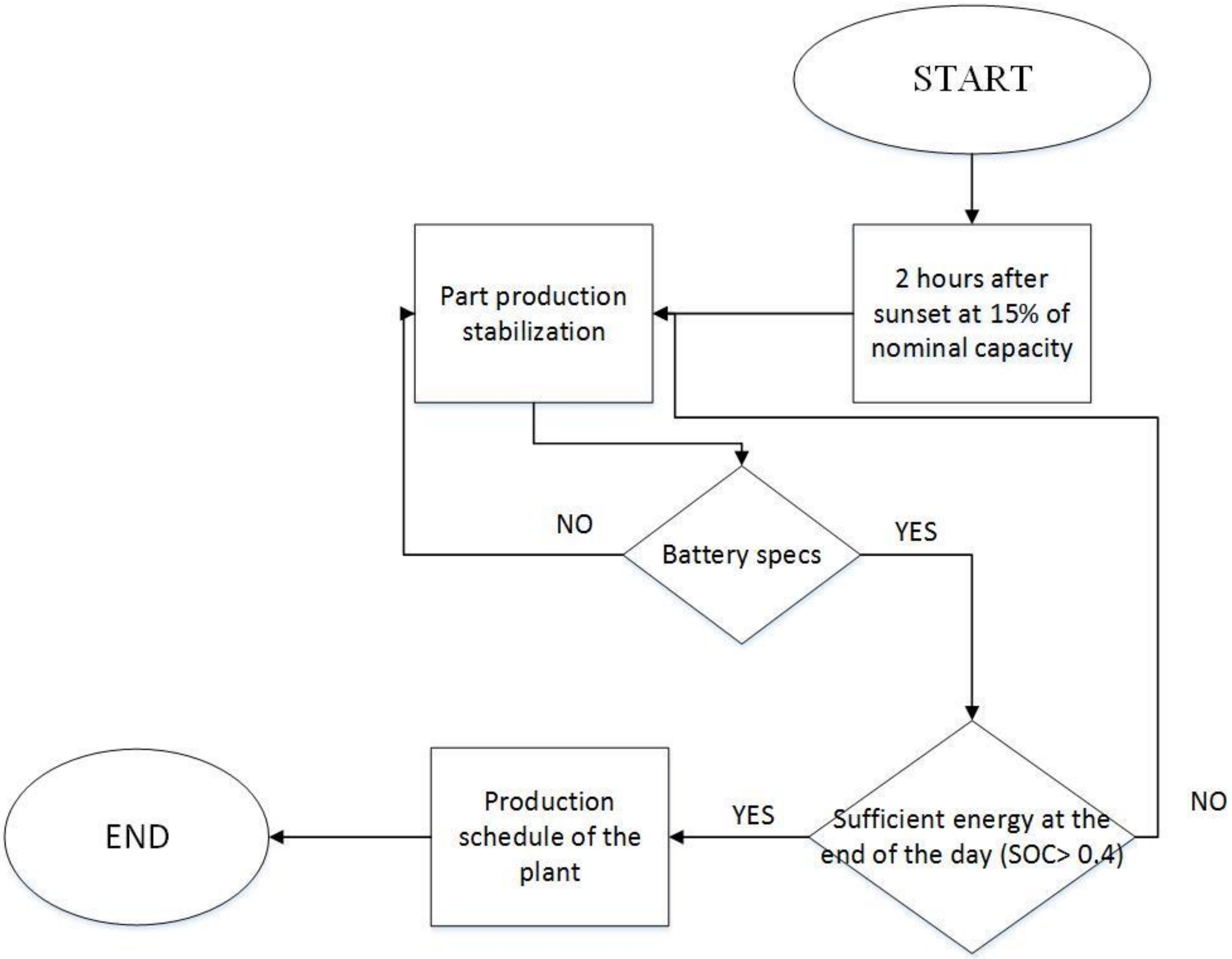

Figure 25: Flow chart of the Duck curve reduction algorithm.

5.5.2 Results

In this section, the difference between the output of the Hybrid Solar-Thermal Park and the output of the Solar Thermal Park alone is computed, exploiting the proposed algorithm. Focus is given on the comparison of the output between the “proposed” operation and the expected “initial” operation based on actual solar data from the meteorological station at the Technical University of Crete.

The ‘duck curve’ reduction expectation is the ‘proposed’ production giving graphs that feature a substantial amount of power production at the time of day around sunset. In a given time period, it is easier to extract conclusions about how much more efficient is the ‘duck curve’ effect minimization. It is important to note that the main point of concern is the solar park to ensure production around the time of sunset.

In the following figures, the production of the park without the addition of the battery bank is presented along with the proposed operation of the park engaging the battery bank, in order to reduce the ‘duck curve’ effect. In the following figures, despite the proposed operation of the power plant, the exchange of power to/from the battery bank and the hourly limits for batteries charging and discharging are shown for each example. These limits, not only take into account the battery characteristics as tabulated in

Table 13: Constant parameters and their values

Symbol	Value
Focal length L	7.45 (m)
Collector surface Ag	87.67 (m2)
Mirror reflectivity γr	0.92
Absorptivity factor IF	0.92
dust losses factor nd	0.98
cavity diameter Acav	0.45 (mm)
Cavity absorptivity acav	0.96
cavity emissivity eeff	0.9
longitude Lloc	24.018 (^{o})
equatorial reference Lst	30 (^{o})
latitude F	35.51
receiver surface Aca	0.2 (m2)
Stirling engine efficiency nload	0.385
Boltzmann constant s	5.67*10-8
converter efficiency nal	0.98

Table 14, but also the state of charge of the battery, as a result of the previously described proposed algorithm. These limits can change depending on the SOC of the battery and its technical limits. In order to examine whether at the end of the day there is enough energy left in the battery bank enabling to employ the same algorithm the next day, graphs of the next day of the examination day, are also displayed.

Examining days throughout a year, a typical day for winter was picked that is the first day of the year. As shown in Figure 26, it is possible to extend the operation of the park at 15% of nominal power by two hours after sunshine and also provide part production stabilization. Furthermore, in Figure 27 it is shown that the same operation is possible for the next day exploiting the amount of energy left at the end of the day before.

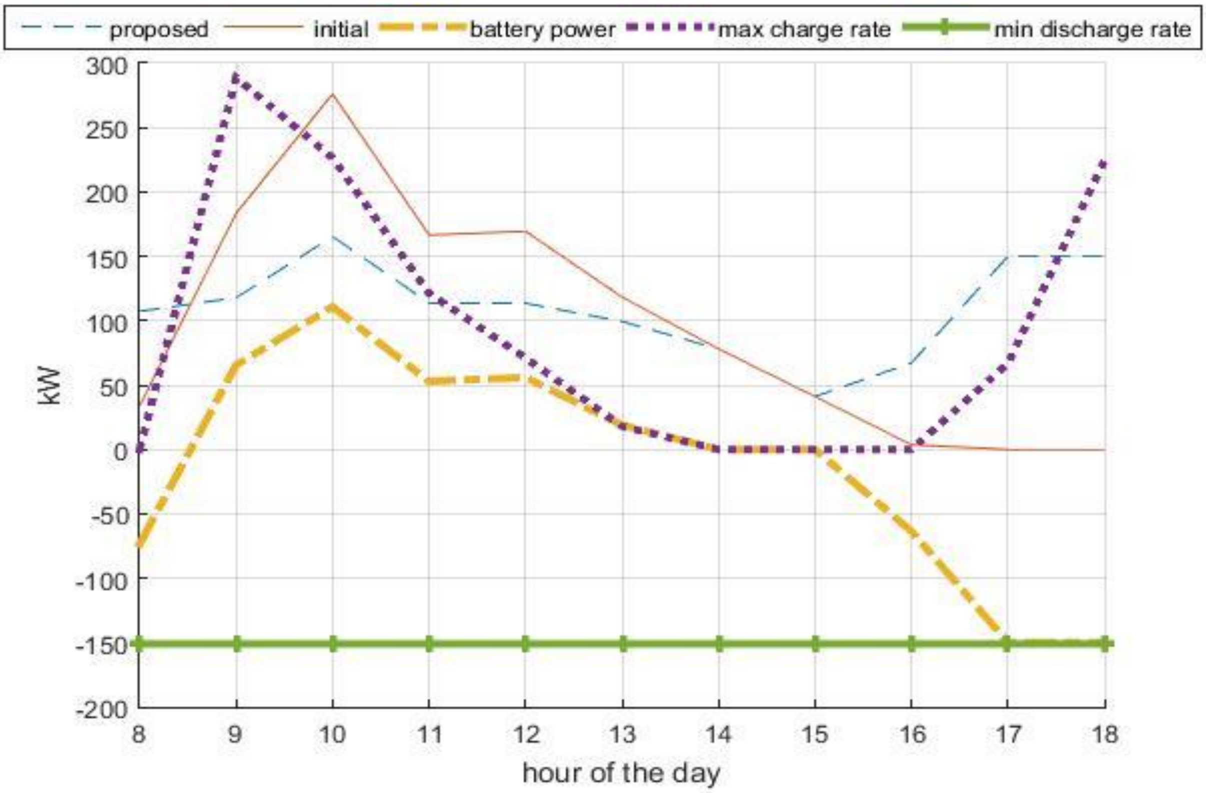

Figure 26: Power production extension on 1st day of the year.

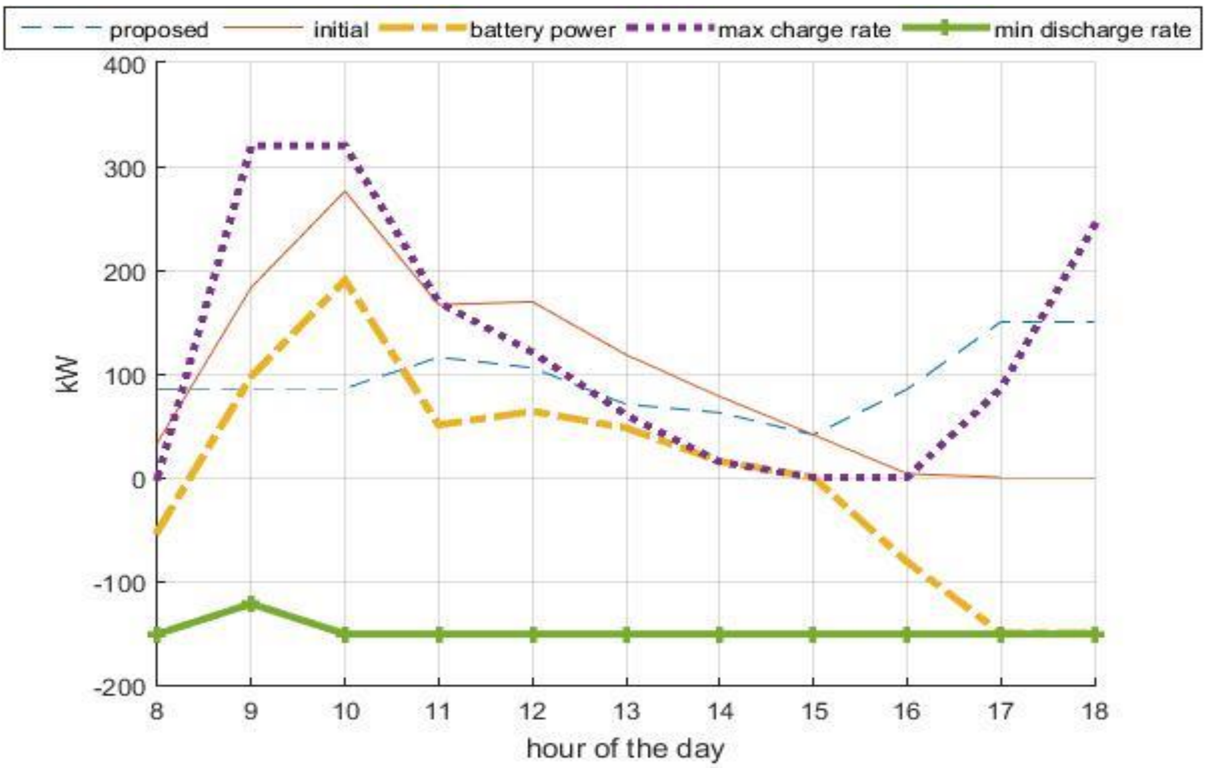

Figure 27: Power production extension on 2nd day of the year.

Since the first day of the year is a low production winter day, a day that has substantial power production is also examined. In Figure 28, a day in December with high solar radiation is displayed. During this day, not only the power production extension is possible, but also there is enough energy to provide for the next day, which is displayed in Figure 29.

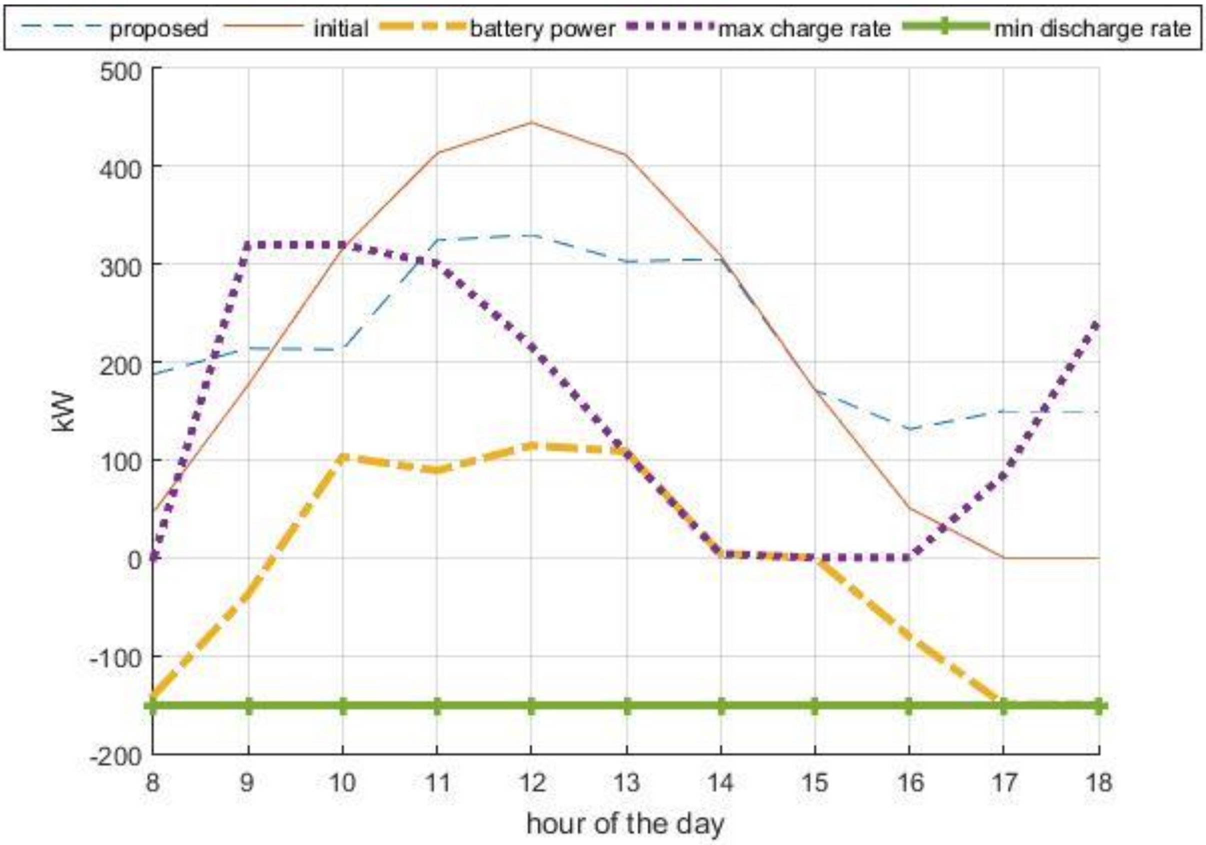

Figure 28: Power production extension on a typical winter day.

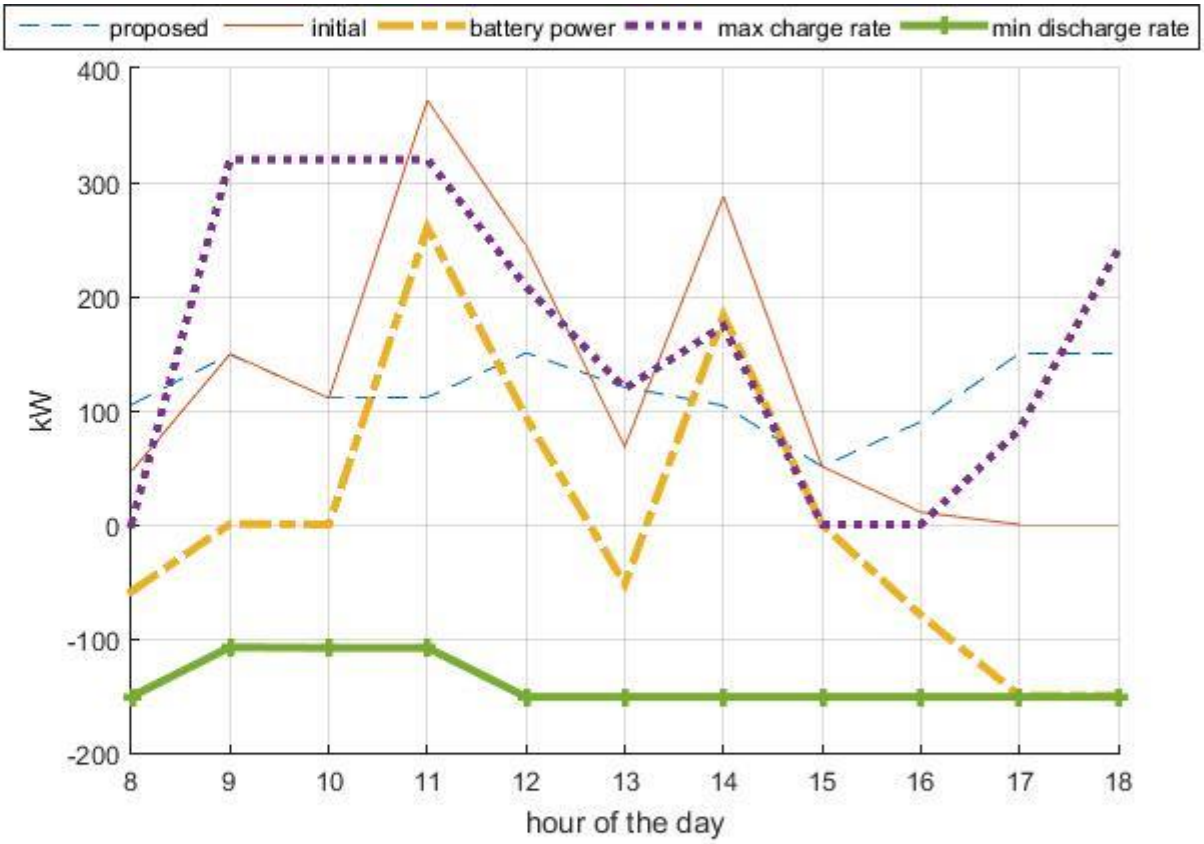

Figure 29: Power production extension for the next winter day.

Examples are also elaborated for a typical spring day and the day after and the relevant graphs are depicted in Figure 30 and Figure 31 , respectively. Similarly, graphs for a typical summer day and the day after are illustrated in Figure 32 and Figure 33. Both, spring and summer are important seasons for the island of Crete, because they are tourist seasons and the power demand rises. Also, they are the two seasons when the 'duck curve' effect is more evident.

In Figure 34 and Figure 35 a typical autumn day and the day after are presented, where also the 'duck curve' effect reduction can be applied and there is power left so the reduction can occur on the next day also.

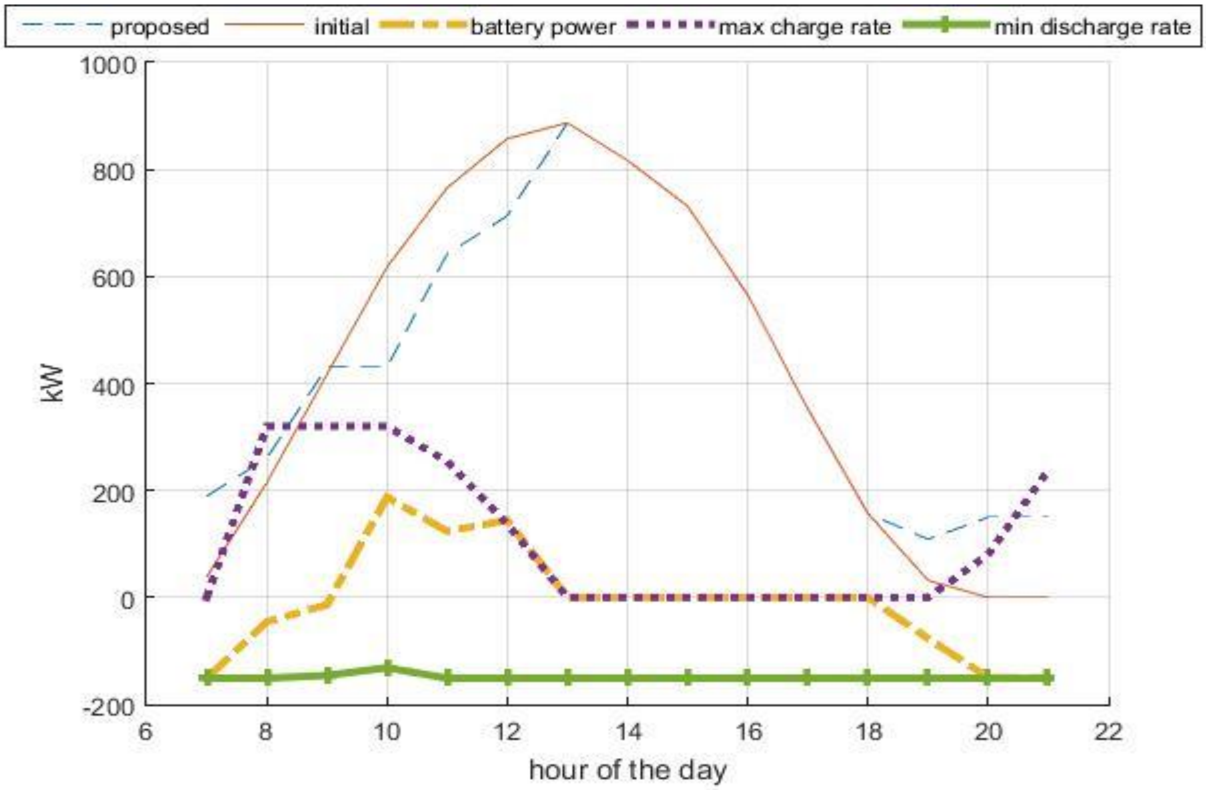

Figure 30: Power Production extension for a typical spring day.

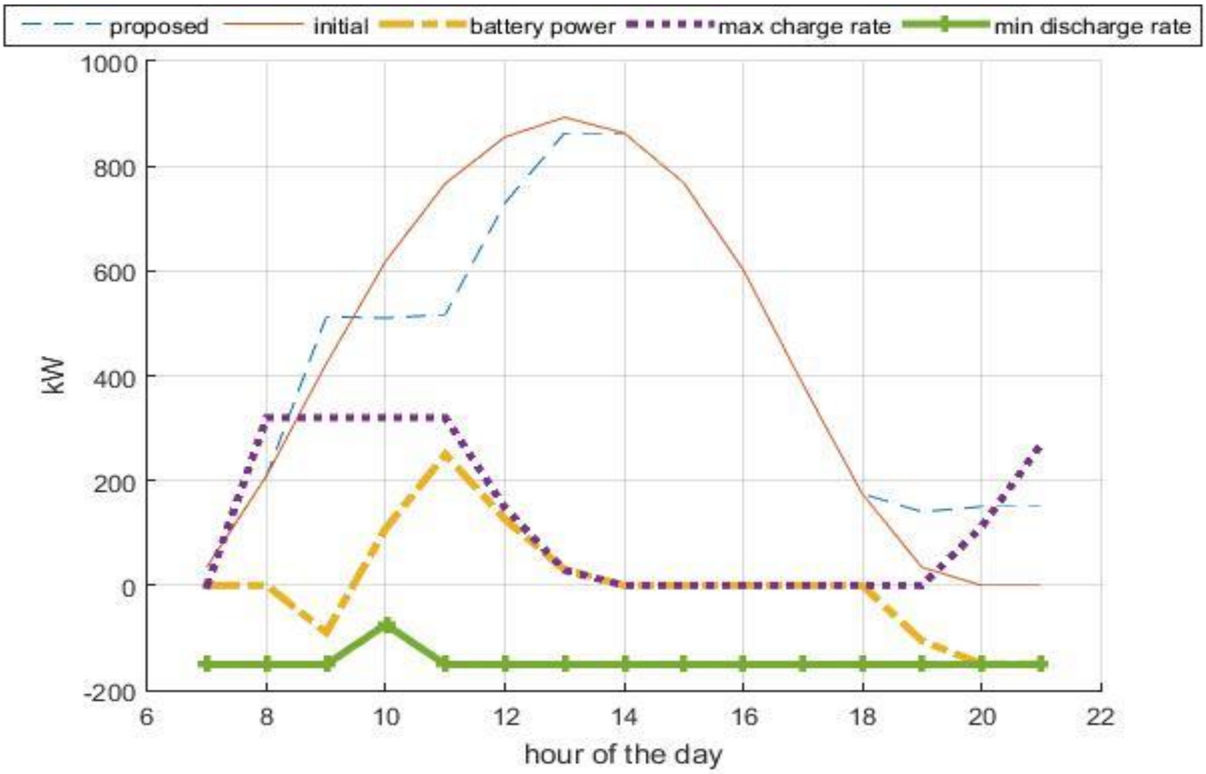

Figure 31: Power production extension for the next spring day.

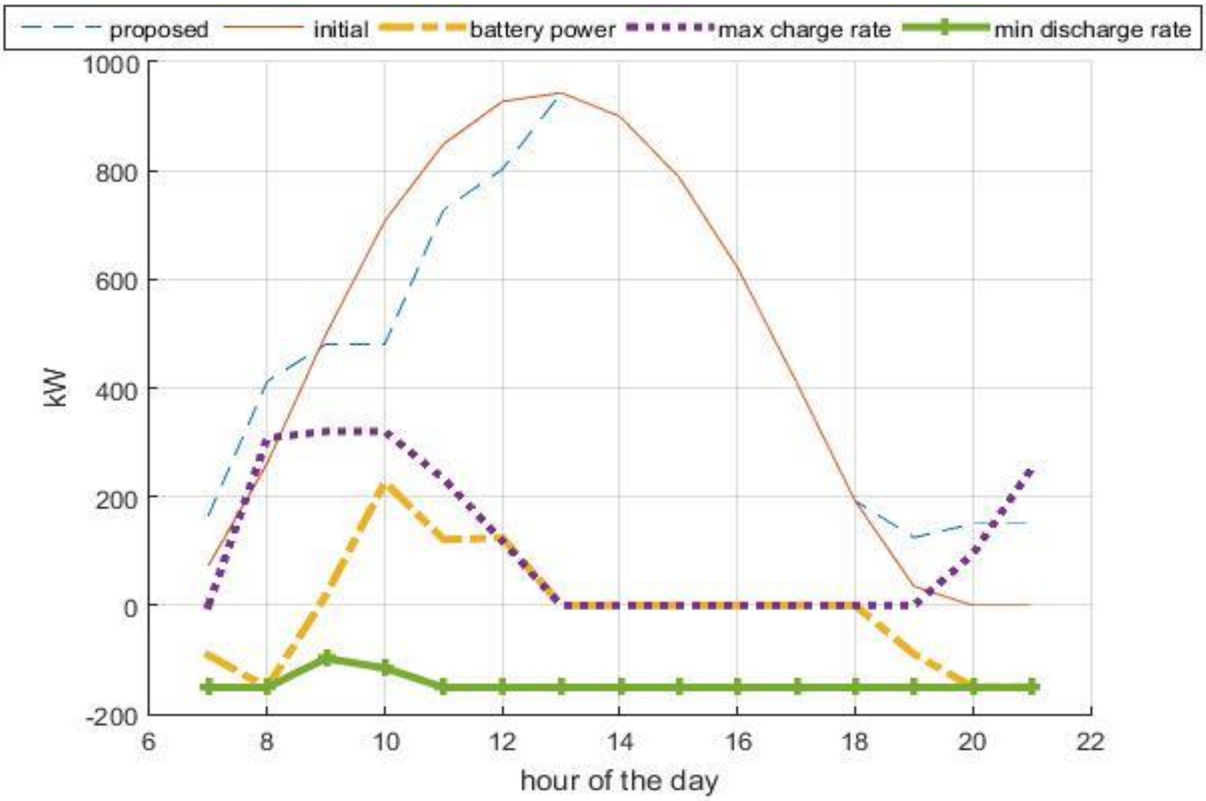

Figure 32: Power Production extension for a typical summer day.

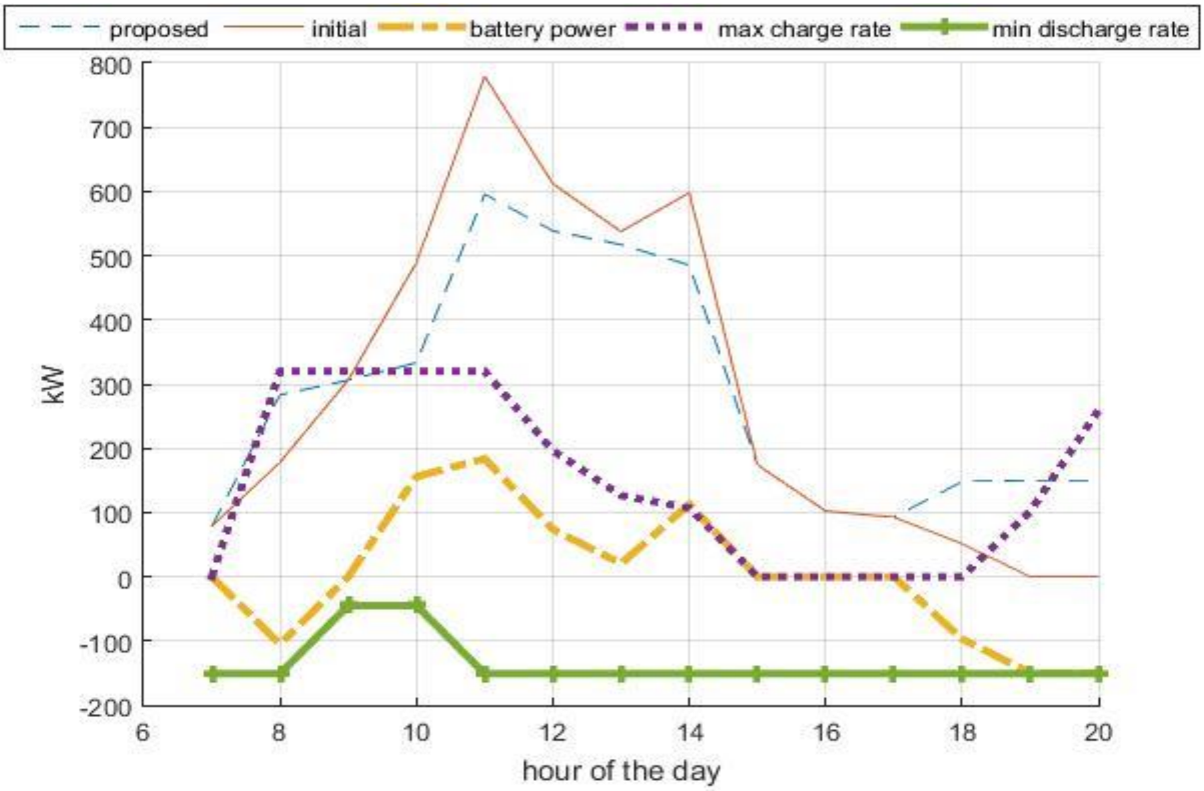

Figure 33: Power Production extension for the next summer day.

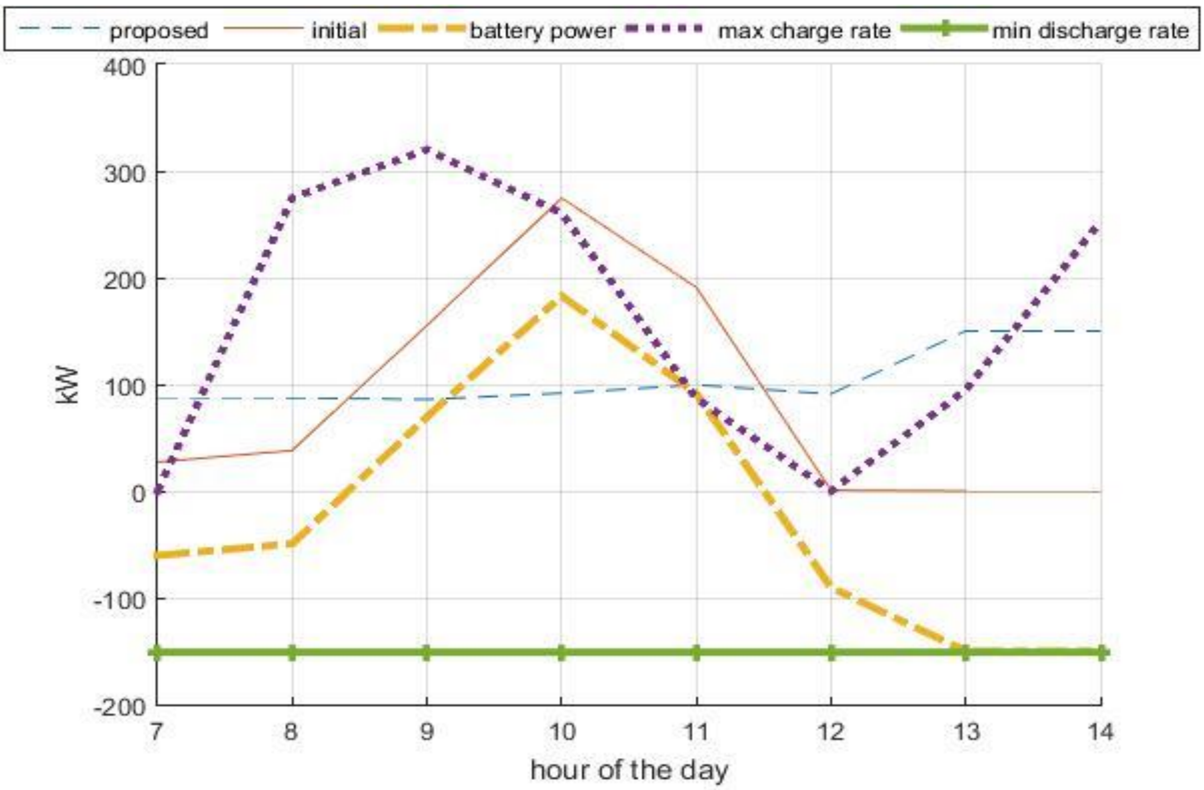

Figure 34: Power Production extension for a typical autumn day.

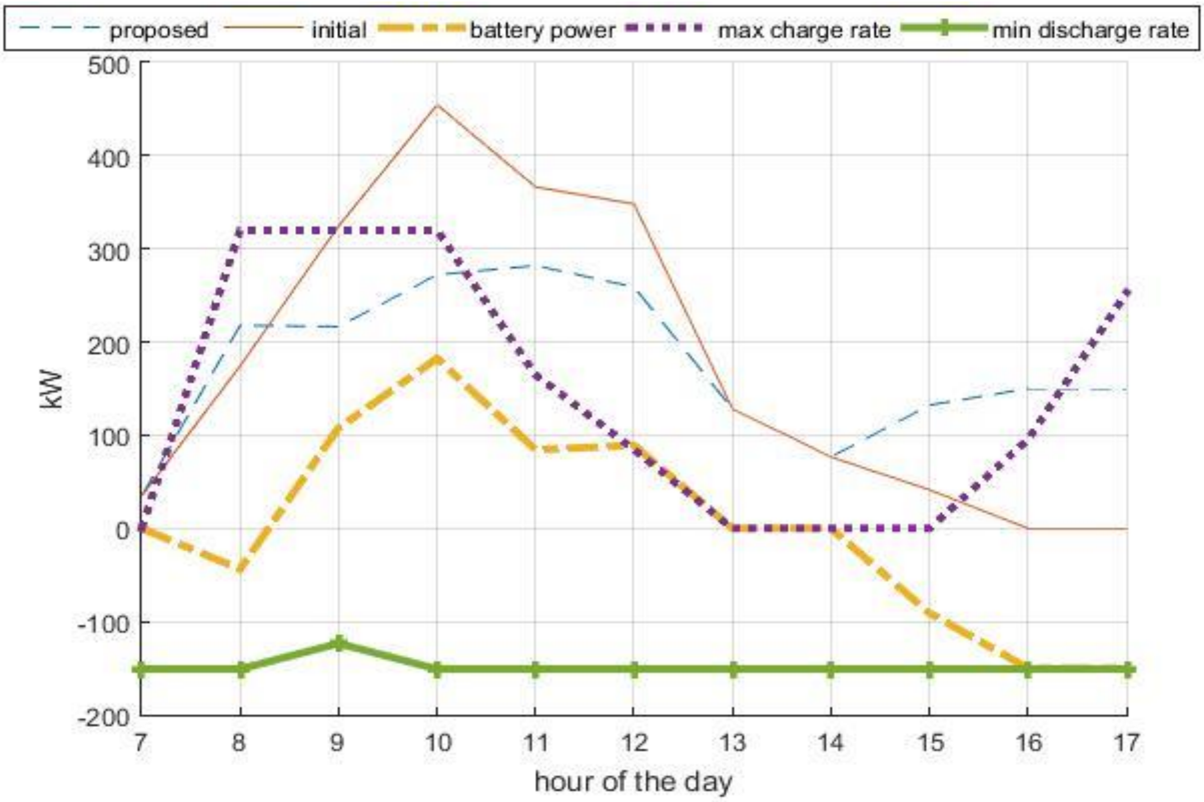

Figure 35: Power Production extension for the next autumn day.

Observing the above figures, becomes clear that by deploying the battery bank, it is possible for a solar thermal power park to extend its operation beyond the hours of sunshine and also the battery bank to retain enough energy to operate during the next day. As mentioned in Chapter 4, the ‘duck curve’ effect occurs in the afternoon hours around the sunset time. The proposed solution described in this Chapter, computes the energy that is stored in the battery bank to provide energy after and around the time the sunset.

In order to examine better if the proposed solution can be implemented for more than a day, the proposed algorithm is tested for the computation of a proposed operation of the solar park for a whole week. As case study, the first week of the year is selected. As shown in Figure 36, the proposed solution is viable for a great number of days, engaging the proposed algorithm day by day. Also, the battery bank retains enough energy left at the end of the week, thus the proposed operation can be implemented for the next week too.

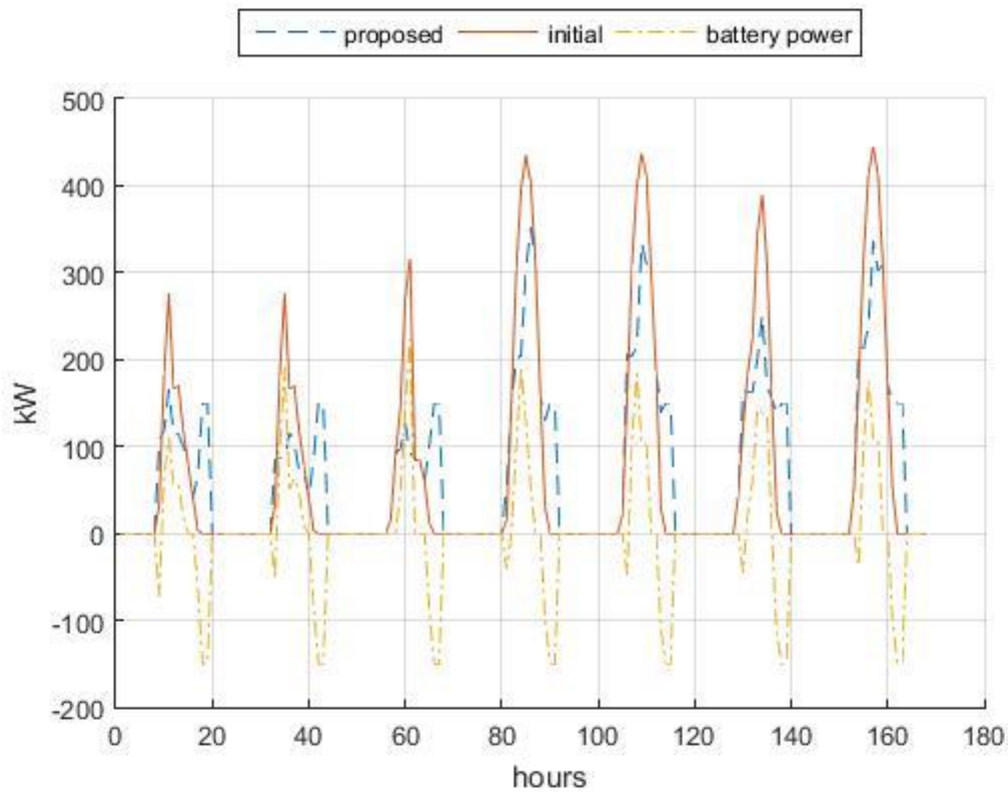

Figure 36: Extended operation for a typical winter week.

The proposed operation of the Hybrid Solar power park with the utilization of battery bank, which is displayed in the figures above, provides a solution to diminish the ‘duck curve’ effect. The proposed operation of the solar park assists the power grid operator for the power production transition to conventional fuel powered units, because by providing energy at late afternoon hours the ‘duck curve’ is not as steep as before, as is described in Chapter 4. The demand at this time of the day can be covered easier and maybe without engaging any more units if this technique is employed by all the sun based RES.

6 Measuring requirements in CSP units

In Chapter 3 of this thesis, regulations and incentives for viable CSP construction have been discussed. As shown in Section 3.1, many countries, like Algeria and Greece, have regulations that provide different tariffs for owners, depending on the usage of conventional fuels. Especially in the Greek Code, CSP producers cannot produce more than 20% of their overall energy production by conventional means. Moreover, in the capacity credit mechanism, the grid operator must have information about the operation and total power production of the units participating in the mix.

So there lies a question of how the power grid operators can monitor the operation of a CSP power plant and how their production is verified and thus remunerated according to their electricity production mix. Except for the regulations for the purchase of power production, there are also regulations that dictate the operation of the power plants. This operation surveillance can be achieved by the installation of measuring units at various points in a CSP power plant, which are related to their operation.

There are not a lot of regulations regarding the measuring requirements that CSP owners must install. Power grid operators around the world rely on instruction manuals for their own measuring requirements and the data that the owner must provide to them, for the power grid to operate as efficiently as possible. Unfortunately, this information is not always freely distributed. In this section, the general concept of measuring, the measurement guides of the European Union, under European Solar Thermal Federation, as well as PJM grid operator and the related Greek ones are presented.

6.1 Measuring devices

Because the measuring requirements are discussed in the present Chapter, it is important to know how these measurements are recorded and the components of the various measuring equipment. Regarding measurements in CSP power plants, in order to measure the thermal energy used, or the fuel supply to conventional units, flow meters must be used as along with temperature sensors. Data from these type of meters, which are installed in various points, can be send to a processing unit which calculates the energy exchange between the stages of production in a CSP power plant, and what comprises the total electricity that is provided to the grid.

6.1.1 Flow measurement devices

Thermal energy inside a CSP power plant is usually transferred from the solar panel field to the generator providing power output through a liquid mean, as shown in Chapter 2. Thus, in order to determine the energy mix of a CSP the use of flow meters is necessary. There are four kinds of flow meters: electromagnetic meters, ultrasonic meters, turbine meters and meters with driven impeller.

6.1.1.1 Electromagnetic meters

The operation of this type of meters is based on the Faraday's law of induction. A constant-strength magnetic field is generated by two field coils, one on either side of the measuring tube. The conductive flowing fluid is the moving conductor. Two measuring electrodes on the inside wall of the tube are at right angles to the coils and detect the voltage induced by the flowing fluid and the magnetic field. The induced voltage is proportional to flow velocity. Taking into account that the tube is of known intersection, the volume flow is finally proportional to the induced voltage.[38]

An electromagnetic meter has advantages and disadvantages. The advantages are:

- The measurement does not depend on other factors, such as the temperature, the pressure, the density and the viscosity of the fluid
- The flow of the fluid is not affected by the measurement
- There are not moving parts
- The meter need little to no maintenance

The disadvantages are:

- The fluid under measurement must be electrically conductive
- The fluid must not contain charged particles
- The pipe must not be electrically conductive

In Figure 37 an electromagnetic flow meter is displayed.

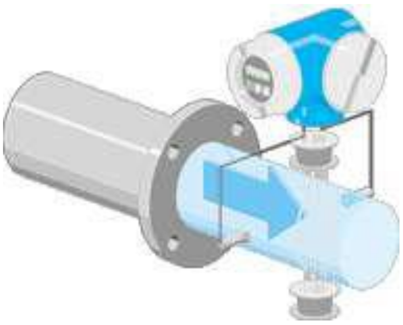

Figure 37: Electromagnetic flow meter

6.1.1.2 Ultrasonic meters

The operation of this type of meters is based on the operation of two sound sensors (transmitter/receiver) that are placed diametrically opposed the pipe conducting the liquid. One of the sensors transmits a sound wave while the other sensor receives with a delay (transit time). Then the opposite procedure is repeated. The difference of the two transit times is related to the velocity of the liquid flowing the pipe. Taking into account that the tube is of known intersection, the volume flow is finally proportional to the transit time difference. [38]

Ultrasonic meters have advantages and disadvantages. The advantages are:

- The measurement does not depend on other factors, such as the temperature, the pressure, the density and the viscosity of the fluid.
- The flow of the fluid is not affected by the measurement
- The measurement can take place in any type of pipe
- The ultrasonic meter can be portable
- There are not moving parts
- Long lifetime

The disadvantages are:

- The measurement is affected if the liquid contains particles
- The measurement is affected by thicker liquids like HFO fuel

In Figure 38 an ultrasonic flow meter is displayed.

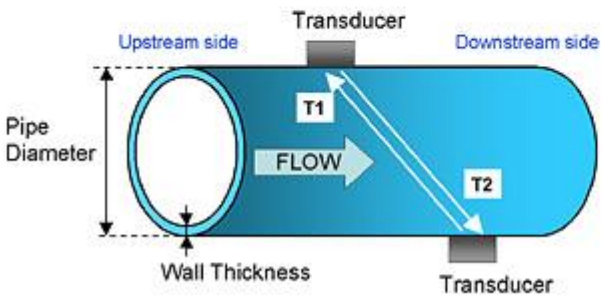

Figure 38: Ultrasonic flow meter

6.1.1.3 Turbine meters

In this type of meters, a turbine is installed inside the pipe conducting the fluid. The fluid flow causes the turbine rotation. The rotational speed is proportional to the fluid flow rate.[38]

Turbine meters have advantages and disadvantages. The advantages are:

- The measurement does not depend on other factors, such as the temperature and the pressure of the fluid
- Besides liquids, they can also measure the flow rate of steam or other gases
- They can operate in all ranges of temperature

The disadvantages are:

- They need to be maintained frequently because of corrosion
- They cannot detect small flows that cannot move the turbine
- They affect the flow of the measured fluid
- They cannot be installed in every type of pipe

In Figure 39 a turbine flow meter is displayed.

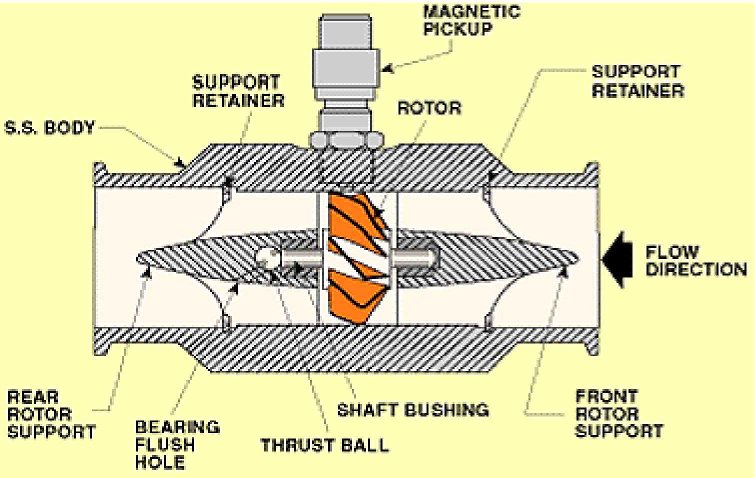

Figure 39: Turbine flow meter

6.1.1.4 Meters with rotating impeller

The operation of a meter with rotating impeller relies on the same principle as the turbine meter. The main difference is that, instead of a turbine, a small impeller is installed inside the pipe, which obeys the same operation and measuring principle as the turbine. A rotating impeller meter features the same advantages and disadvantages with the turbine meter, with the only difference being that the meters with rotating impeller can be installed in more pipe types than turbine meters, because of their smaller size.[38]

In

Table *17* a summary of all flow measuring devices, and the advantages and disadvantages of each, are presented.

Table 17: Advantages and disadvantages of flow meters

Type of flow meter	Advantages	Disadvantages
Electromagnetic	• Measurement does not depend on external factors • Measurement does not affect the flow • Little to no maintenance	• The fluid must be electrically conductive • The fluid must not contain charged particles • The pipe must be part conductive
Ultrasonic	• Measurement does not affect the flow • Any type of pipe can be used • Long lifetime	• The measurement is affected if the liquid contains particles • The measurement is affected by thicker liquids like HFO fuel
Turbine	• Measuring liquid, steam or other gas too • Measurement not depended on external factors • They can operate in all ranges of temperature	• Frequent maintenance • Cannot detect small flows • They affect the flow of the measuring mean • They cannot be installed in every type of pipe
Driven impeller	• Measuring liquid, steam or other gas too • Measurement not depended on external factors • They can operate in all ranges of temperature	• Frequent maintenance • Cannot detect small flows • They affect the flow of the measuring mean • They cannot be installed in any type of pipe

The electromagnetic and ultrasonic sensors are better for measuring the flow of the liquid used as means of thermal energy transfer, because it is a clean and conductive liquid and also because they can measure lower flows than other meters. Turbine flow and rotating impeller meters are most commonly used in measuring the flow of the oil used to power the conventional power units, because the flow is relatively high and the flow of the oil is not affected by the turbines.

6.1.2 Thermal measurement sensors

For the accurate measurement of the thermal energy amount, as well as other parameters that determine a CSP's power plant operation, the measurement of temperature is essential. The temperature measurement in a CSP power plant is based mainly on three types of sensors: resistance temperature sensors, thermocouple thermometers and calorimeters. Of course, there are other types of temperature sensors, but these three are usually used in power plants. The temperature to be measured is between 300 – 500 ^{o}C.

6.1.2.1 Resistance temperature sensor

A resistance temperature sensor is an electronic circuit that consists mainly of a resistance, whose nominal resistance factor changes depending on the area that is placed. The change of its resistance is proportionate to the temperature of the environment it is placed in. So, the temperature of the area around the resistance can be calculated by measuring the current that traverses through the resistance. [38]

A resistance temperature sensor has advantages and disadvantages. The advantages are:

- Fairly good accuracy
- Large output signal that can be used in other applications immediately

The disadvantages are:

- The measuring device has short lifetime
- Accuracy is proportional to the age of the circuit

6.1.2.2 Thermocouple Thermometer

A thermocouple (TC) consists of two wires of different conductive material, connected each other by means of two junctions forming an electrical circuit. If one junction is at temperature T1 and the other at T2, then an electromotive force is generated in the circuit, and it depends on the materials and temperatures T1 and T2 (Seebeck effect). In an industrial TC thermometer one junction is the measuring joint, and the other is a reference one which is usually located in correspondence of the conversion electronics (transmitter).[38]

A thermocouple thermometer has both advantages and disadvantages. The advantages are:

- Good accuracy and response time
- Wide measuring range
- Easy to connect to other systems

The disadvantages are:

- Needs more space to install than the resistance sensor
- It does not operate in low temperatures

6.1.2.3 Calorimeter

The operation of calorimeter is based on measuring the thermal energy of the fluid between two points, in order to determine the thermal energy that the fluid carries. By using two temperature sensors before and after the nozzle of the pipe and a flow meter, the thermal energy transferred by the fluid can be calculated using these two different temperature measurements and the flow rate. . [39]

A calorimeter has both advantages and disadvantages. The advantages are:

- High accuracy at minimum flow rate
- High sensitivity and dynamic response
- Small dimension

The disadvantages are:

- High cost
- Accuracy depends on the flow
- Low range of results

To better understand what a calorimeter is and the parts it is comprised by Figure 40 is presented.

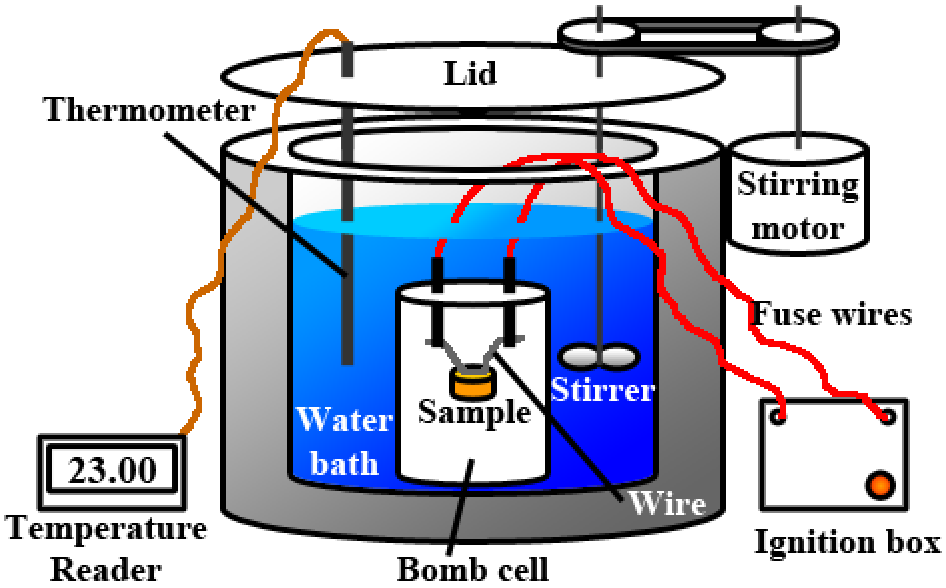

Figure 40: Calorimeter composition

6.1.3 Electricity meters

Electricity meters measure the electric energy that passes through a wire by measuring the amount of energy transferred at a period of time. The electricity is measured by this type of unit in Wh, or multiples of this unit, for higher consumption (like KWh etc.). There are a lot of types of electricity meters. They can operate on DC or AC current, be single phase or three phase and be able to measure the energy that is exchanged by the power grid at a certain point. [40]

The latest types of electricity consumptions meters are called Smart Meters and they are an essential part in every smart grid installation. Smart meters have the ability to measure the electricity that is consumed and/or produced in the point of installation, i.e. in a small building like a house, and also to receive data from electricity production of power producers, in order to calculate the best available energy consumption strategy.

Bi-directional electricity meters are those that are used in power grids usually, in order to measure the energy produced and consumed at a certain point. Also electricity meters that are used in power plants and power grids must be able to measure large amount of electric energy in a relative small margin of time, of around 15 minutes. Except for measuring electricity active power in kW (or larger scale), electricity meters that are used in power grids must also be able to measure reactive power in kVAr (or larger scale). It is important for power grid operators to know the power that is absorbed by the grid in order to cover the demand but also to monitor the reactive energy in the grid. Reactive energy is consumed at the transmission lines and the consumers and thus, it has to be produced by the units. It is also important to monitor reactive power, because the generation of reactive power limits the power grid unit's active power production and may as well, because voltage drops in certain areas.

The electricity meters installed in power grid points must also be able, using the measurements of active and reactive power, to compute the load curve, which is the graph of the consumers' consumption. Load curves are calculated in a time span of a day and they are stored later. New load curve data is used to update the load curve, areas of the grid and the grid as a whole. Load curves help power grid operators to make better energy demand management and also to calculate the operating schedules of the power production units better.

Except for all the above the electricity meter has an optical port or can run a wireless transfer protocol in order to transfer the data gathered to a central location, such as a central monitoring system like SCADA, for further processing.

It is important to note that before the connection of the electricity meter, a metering transformer is used to lower the voltage or current level in order to protect the meter and also any concerning party form danger. The meters also have ports, like optical ones, to enable data exchange with a center point of control.

The measuring quadrants that the electricity meters must operate on are shown in Figure 41, and the connection of a three-phase meter to the supply or production is shown in Figure 42. [41]

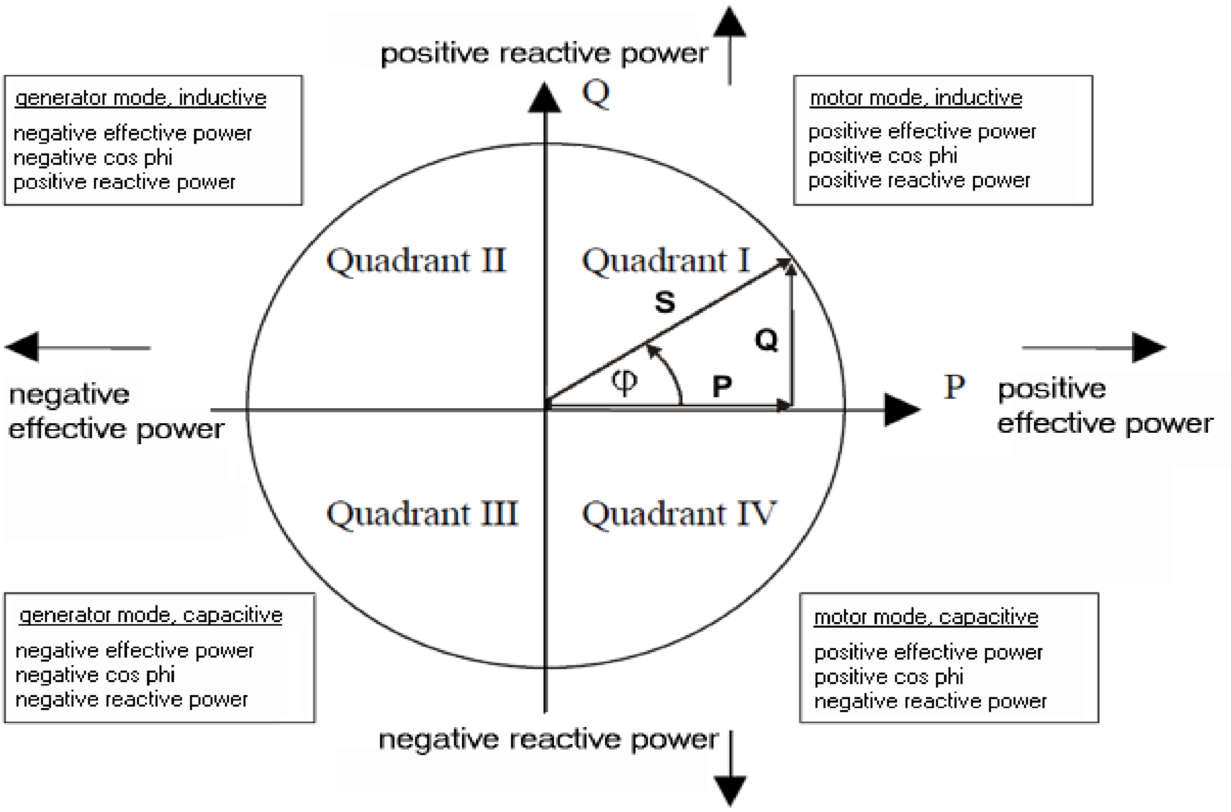

Figure 41: Measuring quadrants

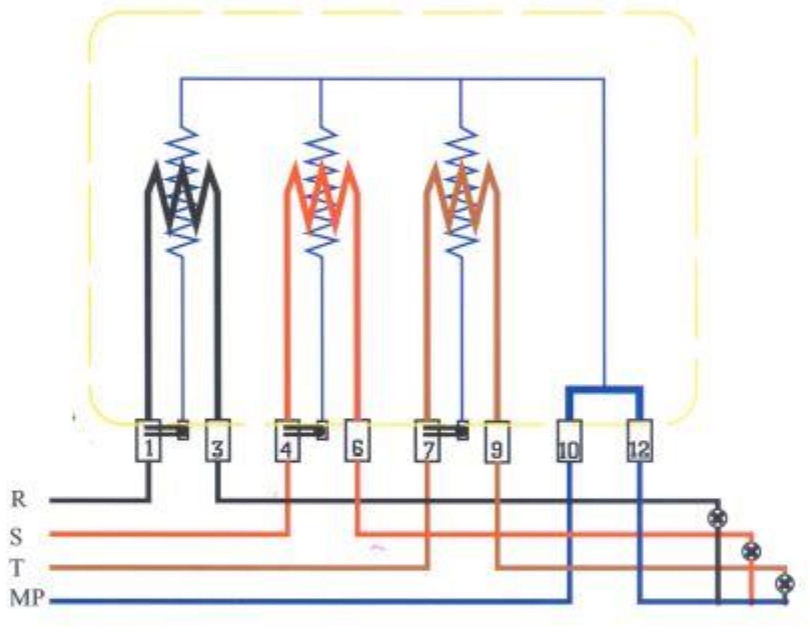

Figure 42: Three-Phase electricity meter connection

6.1.3.1 Measuring Transformers

Measuring Transformers are electrical devices that are used to transform the measuring figures, which are usually really high, to a range that the measuring units can detect and to protect them from possible damage. These transformers are essential for measuring units because without their installation the measuring process cannot take place. Transformers are usually installed before the connection point of the measuring device and are divided in two categories: voltage and current transformers.

Voltage transformers are used to demote the voltage usually to 100 V in order for a safe measurement to take place. There are two kinds of voltage transformers, single-phase and double-phase. Double-phase transformers are most commonly used in power grids because only one of them can measure all 3-phases of the grid.

The current transformers are used when the current flowing through the connection point is higher than 100 A. This type of transformers are used because it is not yet possible for measuring units to directly measure this level of current. Current transformers are usually round, or ring shaped and the output current they provide must be at 5 A maximum.

The connection of a measuring unit transformer is displayed in Figure 43.

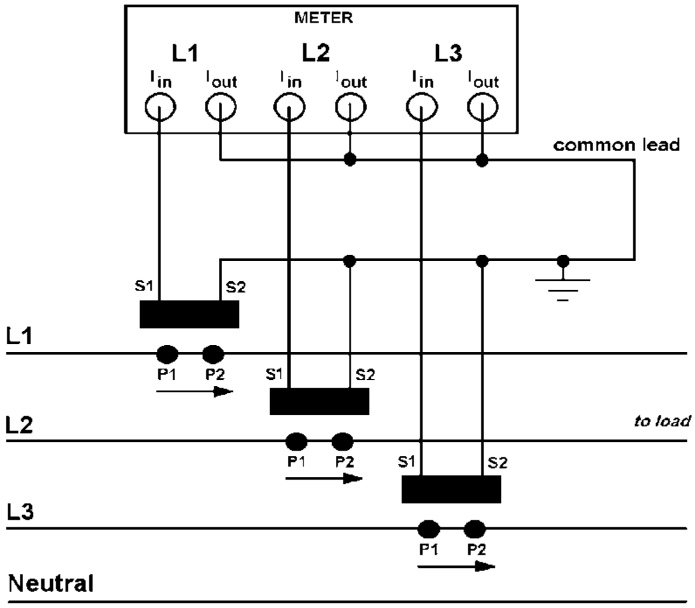

Figure 43: Connection of a measuring unit transformer

Finally the measuring unit's transformers are categorized based on their specified class of accuracy. The class of accuracy determines the threshold values of the rated load at which the error of the transformer is within under certain margins. The accuracy class of the transformers is shown in Table 18.

Table 18: Accuracy class of measuring unit's transformer

	Accuracy Class				
Current Transformer	Kl 0.1	Kl 0.2	Kl 0.5	Kl 1	Kl 3
Special Category		Kl 0.2S	Kl 0.5S		
Ext 200	Kl 0.1G	Kl 0.2G	Kl 0.5G	Kl 1G	
Voltage Transformer	Kl 0.1	Kl 0.2	Kl 0.5	Kl 1	Kl 3

Where:

S – Class of current transformers of measuring units of voltage with ratio trends of 25/5, 50/5 and 100/5 and nominal current of 5A and it is referring to electronic measuring devices that their accuracy is proportional to currents between 50mA and 6A (namely 1% and 120% IN=5A)

G- Class of current transformers that can operate with twice the input current I_N than the S-class ones and can maintain the accuracy class between 0.005 to 2 times the input I_N. The G-class transformers are used in cases where the load has multiple variations.

6.2 Measuring devices specifications

Measuring is important not only for the operation of a CSP power plant but also for all the various stakeholders concerned. The data gathered by measurements help the producer to adjust and optimize the CSP's power production and also to approve the payment he receives. The power grid operator needs the measuring data for:

- The power production scheduling of the rest units in real-time
- Smooth operation of the power grid
- Remuneration of power production
- Fines for non-compliant operation

The data needed by the producer is collected after the installation of the appropriate measuring devices at the appropriate spots of the CPS power plant. The appropriate measuring spots in the power production sequence of a CSP plant are often determined by the producer, but in most cases the power grid operator may also acquire data from the units participating in covering the load. This data also provides information to the operator in order to charge the correct amount to the power production producers without any doubt.

It is common for the grid operation regulations, especially in isolated grids or non-interconnected islands, to contain instructions to producers about both, the measuring devices specifications and what data exchange is required. The data obtained by measurements can help the power grid operator to maintain the level of integrity to the grid and also determine the payment of the power producer that depends on the type of power he produces (RES, with conventional fuel etc.)

6.2.1 Measuring devices specifications in Greece

As mentioned above, the specifications for measuring devices are important in determining the data needed for a CSP power plant to operate. In order to meet measurement requirements, power grid operators have specifications for measuring devices, which are obligatory for any power grid in Greece from the moment a power plant is connected to the grid.

Obligatory specifications for measuring units are included in the non-interconnected island Greek code, mainly because isolated grids are more difficult to operate, and the remuneration of power produced is based on energy balance between RES and fuel powered units. All the specifications are included in the Measurement and Measuring Devices Manual of Independent Power Transmission Operator (IPTO) thus also applies to Hellenic Distribution Network Operator (HEDNO) that is the sole operator for non-interconnected islands. [46] Not only do the specifications refer to the measuring devices, but also to the other elements that must be installed in order for the power plants to operate smoothly. This data can be accessed by all stakeholders concerned. Specifications are also important for the charging mechanism of each power grid so that the data and the payments are not in doubt by any concerned parties.

Despite all the specifications, it is important to note that every measuring device must be accompanied by a second one to act as a backup in case of failure, so as the power grid operator will collect important data even in a case of failure. [42]

6.2.1.1 Meters installation points

The places where the measuring devices are going to be installed must have the following criteria:

- Be accessible for inspection and gathering annual data by IPTO or HEDNO authorized staff
- Be protected by humidity, dust and over-heating
- They must be installed in places that are not subject to vibrations, or any other interference

The measuring device is placed on a panel or a cabinet, according the position and the size of the device, and it is secured so that only authorized competent staff, enforced by the Code, can access it.

6.2.1.2 Technical characteristics of measuring devices

The basic technical characteristics of the new measuring devices are:

- Three-phase electronic devices with:
    a. three elements – 4 channels
    b. two elements – 3 channels

of active energy (KWh) and reactive energy (KVArh) of asymmetric load.

- The accuracy class of active energy is 0.2 S or 0.5 S and of reactive energy 2 or 3 S
- The devices must be able to measure large amounts of energy and operate in every possible grid and connection point
- The devices that measure energy must be able to measure incoming and outgoing energy in two dimensions of active and reactive energy, voltage per phase, losses in the two dimensions, sum of harmonic distortions in all three phases, the number of voltage drops and power factor.
- All the data is calculated in the spectrum of 1, 5, 10, 15, 30 or 60 minutes. The optimal is to use the spectrum of 15 minutes.
- The devices must have digital liquid crystal display in order to show the measurement with at least 8 digits.
- The devices must be able to exchange data with a central telemetering station with DLMS or similar protocol
- The devices must have storage capacity of 96 time spectrums for 60 days of the measuring element

6.2.1.3 Communication Unit

The communication unit in a measuring device can be installed alongside or not to the measuring device. The data exchange between communication units and the central telemetering station can occur using one of the following devices:

- a PSTN Modem using the public telephone network
- a GSM/GPRS Modem using the public mobile telephone network (3G, 4G)

The communication unit must have two independent ports for communication. The first port must be one of the following:

- RS232 (with minimum speed of 9600 bauds)
- RS485 (with minimum speed of 9600 bauds)

The second communication port can be one of the following:

- Modem V34-PSTN to contact the central station
- Modem GSM/GPRS

6.2.1.4 Communications Protocol

The communication protocol is based on the standard communication protocol DLMS for data exchange, measurements and tariff and load control. All the measuring devices must have a part installed that is compatible to DLMS/COSEM application protocol. The DLMS/COSEM protocol must be able to connect to the measuring device, using one of these available ways like an optical head port, Modem via telephone network, Modem GSM/GPRS via mobile network or electricity distribution lines. The measuring devices must be compatible with all three levels of DLMS communication protocol.

6.2.1.5 Other Equipment

The test box is a device that is part of the measuring device and it is used to test the measuring equipment up close, without the disruption of data flow during this testing. In general the test box is used for:

- Cutting off the voltage from the measuring device terminals
- Testing the measuring device in artificial load
- Replacing the measuring device

6.2.1.6 Synchronizing

Every measuring device is set according to the summer time of the Universal Time Clock (UTC). The clock inside the measuring device provides all the necessary timing for the proper operation of the measuring device. The timing is produced by a Quartz crystal and can be synchronized by an input signal. The synchronization of the measuring devices must be checked daily based on the certification process and control measurement during communication between the measuring device and the telemetering central system, which uses a satellite clock.

Every time stamp must begin inside the time period of ±3 seconds of the actual time. The time stamp must end inside the limits with accuracy around ±1%. The measuring device should accept a synchronization pulse only if the difference between the internal clock and the telemetering system clock is more than 9 seconds. In any other case the synchronization is being done manually.

The internal clock provides the following features:

- display in the date and time display
- timer setting for the tariff zones
- signaling time to load curve, in fuel measuring devices
- creation of the integration period of the load curve, in fuel measuring devices
- Time and date can be modified through the optical port or the RS232 port of the device, or remotely with special configuration software using specific safety standards.

The secondary backup measuring device, which was mentioned at the beginning of the chapter and its installation is obligatory, must be at complete synch with the main measuring device, so in case of a failure the measuring sequence will continue the same way as it did before.

6.2.2 Measuring devices specifications in the world

Except for the Greek Code of non-interconnected islands of HEDNO, power grid operators around the world have also included measuring device specifications in their code, in order to collect data that will help them operate and develop the power grid efficiently.

6.2.2.1 Measuring devices specifications in the USA

In the USA the largest power grid operator is PJM Interconnection (Pennsylvania Jersey Maryland Interconnection) that is responsible for the East coast power grid. This power grid operator despite all the specifications wants to have a general oversight at the power plant from the construction phase till the day is going to shut down. That's why it demands reports from every operation of the power plant including every action to modify the station (auxiliary station, extra generator, change in construction of the station features etc.).[43]

The specifications in the PJM code are not about the measurement devices but about the type of data that must be sent to the power grid operator. The data and the measurement schedule are very specific and the best quality of them is required.[44]

6.2.2.1.1 Data required by the grid operator

The data from each electricity producer is sent to the local PJM operation center of the area, and from this center to the central operation center of PJM, for further analyzing and storing. The data that the power grid operator requires are:

- The operation schedule the units of the plant have and the preferred participation on the power market
- Static data for stability studies of the whole system
- Installation study of the transformer at the connection point to the grid
- Settings of relay and any other safety device
- Generator operating curve and control data
- Specific operating restrictions
- Maintenance program
- Any other data that the producers thinks that will help his case in the power market system, in order for his units to participate in the energy mix

Most of these data are static, meaning they are not often updated, and are provided by the owner to the power grid operator the moment that his power plant is connected to the power grid. Even though these data are static, the power grid operator requires that these are renewed at the beginning of the year, especially the data about generators operating curve.

6.2.2.1.2 Measurement requirements for operation and grid

In order for the owner and the power grid operator to establish a measurement schedule they have to also establish:

- The operation schedule of the power plant including some operation running tests
- The producer's choices on what type of real-time data he must provided
- The producer's business plan regarding the units he owns, especially if he is newly added to the production mix
- The power grid operator's requirements for the producer's power plant operation

In order for the owner of the power plant to meet the last bullet requirements, he must install in all his units measuring devices, and the equipment needed for them to operate, so that the power grid operator has the data required for the power grid operation. Regarding producers that have units with nominal output power less than 10MW they are obligated to provide real-time data 24 hours a day for every day of the year.

For the producers that provide real-time data to the power grid operator the requirements are:

- Real-time measurements of active power (MW) for every unit in the power plant before the transformer in the connection point to the grid
- Real-time measurements of reactive power (MVAr) for every unit in the power plant before the transformer in the connection point to the grid

- Producers with units of nominal power less than 10 MW must also provide data for how close they operate to the technical limits of their units

For the producers that don't provide real-time data to the power grid operator, the requirements are:

- Hourly compensated energy in MWh delivered for each unit
- Hourly compensated energy in MWh entered for each unit
- Hourly compensated reactive energy in MVARh injected for each unit
- Hourly compensated reactive energy in MVARh absorbed for each unit (it is not obligatory at the moment)

Measurements in MVAR will become obligatory when the consumers of the power grid, which shape the load demand of the grid, also produce power in the form of small RES units.

For the producers that have more than one power plants, they must have a central command center, in which they will gather all the data from every power plant they own, so it will be easier for them to follow the power grid operator instructions and apply them to all the units.

In order to meet measurement requirements the installation of measuring devices is necessary. The measuring devices must be installed in the spots mentioned above and must be able to measure active and reactive power with an accuracy rate around 97% and also have an external connection to a network.

Finally, the producers must have connection to a data transfer network (like the internet) in order to be able to send the required data to the PJM operation center of the area, which must have a SCADA system. But before they sent any data to the power grid operator, they must also have provided the following:

- Size of the generator in MW and MVAR measured at the transformer that is connected to the grid
- Maximum generator voltage threshold
- Maximum generator frequency threshold
- Recommended by producer maximum voltage limits and the generator operating current

6.2.2.2 Measuring devices specifications in European Union

The European Solar Thermal Industry Federation (ESTIF) is responsible to provide guidelines to CSP owners that have a CSP in a country in the European Union about the measurement requirements as well as the measuring devices specifications. The measuring devices specifications are established by the program- Key Issues for Renewable Heat in Europe (K4RES-H), provided by the Intelligent Energy Europe Project.[45]

The K4RES-H standard is based on the total useful renewable thermal energy that is produced by the CSP resulting to:

- The thermal energy produced is measured at the first point of production in the CSP plant, the solar panel field, solar tower or solar dish. This measurement does not take into account the losses that occur while the fluid is transferred through the pipes or during the storage of energy. Measurements in solar thermal parks are required only after the thermal receivers or collectors
- If thermal energy is used to help increase the production levels of the CSP is only taken into consideration if it is more that 5% of the total thermal energy of the system

- If in the CSP a biomass burner is used, then the energy required to fuel this device is not taken into account

In order to verify these guidelines and also for the power grid operators to have the data needed, the installation of measuring units is required in the appropriate spots. The thermal measuring devices proposed consist of:

- Flow meter that is used to measure the flow of the liquid that is used to transfer the thermal energy (usually is water)
- Temperature sensors that are used to measure the temperature of the liquid
- Processor to receive the data and calculate the thermal energy transferred.

The flow measuring units as well as the temperature sensors must be of the mentioned at paragraph 6.1.1 and at paragraph 6.1.2 respectively.

The processor unit must be able to receive signals from the installed measuring devices and also have the processing power to calculate the thermal energy transferred. It must also have the capability to connect to a network, like the internet, in order to send the data to a central tele-metering system.

All the measuring devices that are used to determine the thermal power in a CSP have accuracy specifications for maximum tolerance to error that may have. The errors that occur are based on:

- The meters and the sensors that are used for the measurements. For these meters, the error margin is about 2%, or 0.2 S, as mentioned in chapter 6.2.1.1
- Errors based on the data transfer and collection. In this stage the error margin is 3%
- Analyzing the measurement data to calculate the thermal energy. The error margin in this stage is 4%.

Regarding the error margin to a CSP power plant as a whole, it is proportionate to the size of the solar panel total reflective area or the solar dish reflective area they have. All the error margins are presented in Table 19.

Table 19: Error margin depending on solar reflective area

Size of solar field	**Error margin**
Larger than 1000 m^2	2%
Larger than 500 m^2	3%
Larger than 100 m^2	4%
Larger than 50 m^2	5%
Other sizes	10%

6.2.3 Measuring devices installation points

The specifications of the measuring devices are important but it is also important where they are going to be installed, because owners can determine the data they need to gather from the CSP power plant, except the measurements required for determining the payment to the producer. Regarding countries outside Greece, the measuring points about the operation of the power plant that the power grid operators require are not many and obligatory, instead of measurements for determining the payment to the producer that are obligatory. As for the countries in European Union the measurements points in where the measuring devices can be installed are after the solar field and before the point of connection to the power grid.

In the USA the only measuring points required by the power grid operator are before the transformer of the unit that is connected to the power grid. This doesn't imply that the producers cannot install other measuring devices, mainly to monitor the CSP operation. The power grid operator in these cases needs to know how much power is going to be produced by the units and injected to the power grid, in order to operate the power grid as efficient as possible.

In Greece mainly because of the capacity credit mechanism and the 20% energy injection from conventional units in CSPs, the power grid operator needs to have more data and supervision over CSP power plants. Most of the required data is not only used to help the operator determine how much energy was produced by the renewable source and how much by the conventional generation, but also to ensure that the conventional unit generation does not pass the 20% limit. [46] [47]

The Greek Code, as well as the standard contract, include the measuring points that are needed in a non-interconnected island. The points are based on the fact that the power grid operator must inspect whether the producer's CSP achieves the capacity credit factor and if the producer complies with the fuel cell usage limit. If the limit is passed then the producer must pay a sanction to the operator service depending on how much it had surpassed the limit.

The measuring points in a CSP power plant are:

- Thermal energy measuring devices, calorimeters if liquid transfer is used as heat transfer medium and pressure gauges, volume and temperature in case of the use of steam at the solar heating field. The actual points are before and after the solar boiler in solar tower CSPs, at entrance and exit points of the solar field in parabolic trough or Fresnel collectors CSPs and at the thermal receiver and before the input of the Stirling engine at solar dish CSPs. (In the figures following the text the points are marked as 1 and 2)
- Similar to previous devices before and after auxiliary fuel boilers, if they exist, to determine the contribution of these to total heat production. (In the figures following the text the points are marked as 3 and 4)
- Fuel metering devices to each boiler of auxiliary fuel, if they are installed, and also in any generation set of the power plant, in case it is requested by the power grid operator to accurately identify (or confirm and control) the participation of auxiliary fuel units in total production of the power plant. In this case, the producer must submit to the power grid operator dully certified specific fuel consumption curves. (In the figures following the text the points are marked as 5 and 6)
- Electricity measuring devices produced at the output of any installed generator sets.
- Electricity supply measuring devices of auxiliary consumption of the station, where it is needed, and electricity measuring devices for own consumption when they are powered by an independent supply of LV grid. (In the figures following the text the points are marked as 7 and 8)

The requirements of the points of measurement are plenty in the Greek code so it is important here to remember why that is. As mentioned before, the non-interconnected island code provides capacity credit payments. With this paying mechanism, RES owners can have more economic benefits from the units they own, if during their operating hours can have power production over a threshold that they can set themselves. This actions lead to a more stable production from RES units. To have that stability in the production they can use power production from a conventional fuel generator, either in the process of obtaining heat or the total power output.

This power production enhance, in order to maintain the renewable factor of the station, cannot exceed the 20% of the total energy produced by the station a year, either on heat enhancement or total power output. For this reason it must be absolutely ascertained where the extra power production comes from, so as the energy balance to be calculated and the power grid operator can determine if the producer complies with all the requirements.

In Equation (35) the mathematic formula that calculates the energy produced by conventional fuel is presented.

$$E_{G,conv} = \frac{Q_{conv1} + Q_{conv2} / \mathrm{n}}{Q_{sol} + Q_{conv1} + Q_{conv2} / n} \cdot \left(E_G - E_{G,HZ} \right) + E_{G,HZ} \qquad (35)$$

where:

$E_{G,conv}$ is the energy produced by conventional fuel

Q_{sol} is the thermal production of the solar field

Q_{conv1} is the thermal production of the conventional fuel added to the liquid thermal transfer mean

Q_{conv2} is the thermal production of the conventional fuel added to enhance the steam

n is the efficiency of the power transformer between the solar field and the steam thermal cycle

$E_{G,HZ}$ is the energy produced by other generation sets

E_G is the energy produced by the station that is measured at the grid connection point

The total participation of energy production by conventional fuel is calculated as shown in Equation (36).

$$\lambda_{conv} = \frac{E_{G,conv}}{E_G} \qquad (36)$$

From the above it is derived why the Greek code of non-interconnected islands requires so many measurements and why that these measurements are essential to the way the power grid operates and the energy production payments are made. At this point, it is important to note that instead of conventional fuel, biomass can be used as an external source of energy to the CSP power plant. Regarding biomass fuel, if it is used to the CSP hybrid mode, then the total energy output that a generator powered by biofuel is also 20%. [46]

In the following figures all types of CSP power plants are presented alongside the requirement measuring point, which are numbered as explained in the bullet point above.

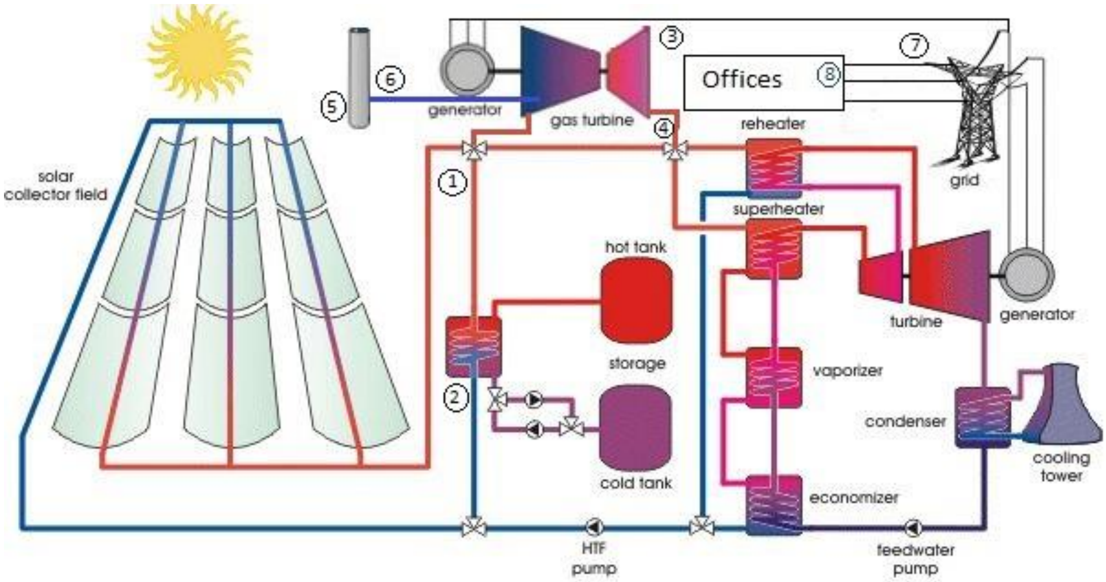

Figure 44: Measuring point in a parabolic trough CSP

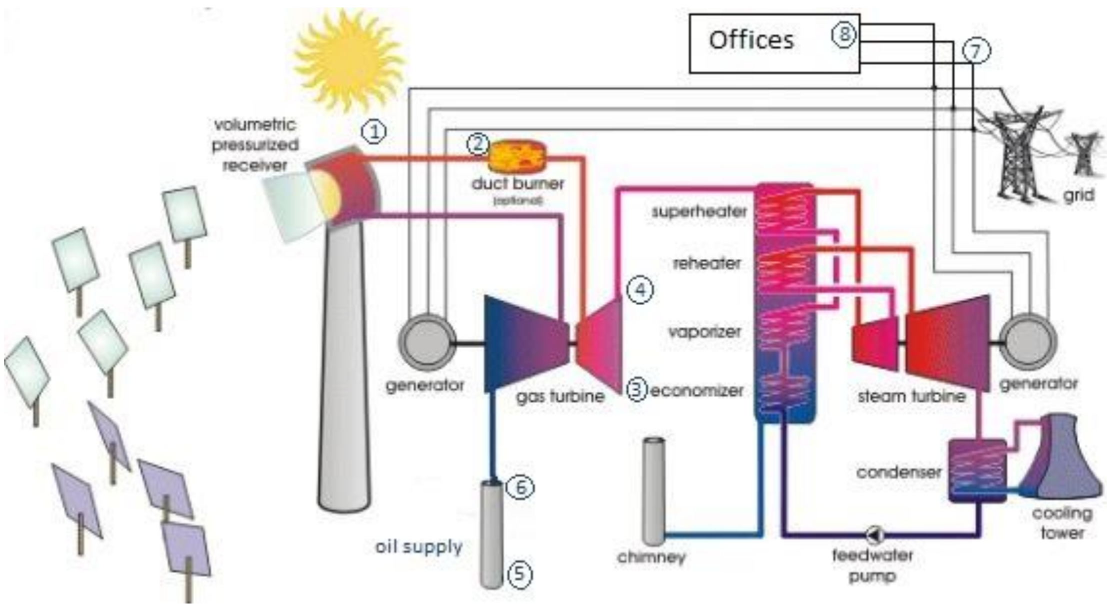

Figure 45: Measuring points in a solar tower CSP

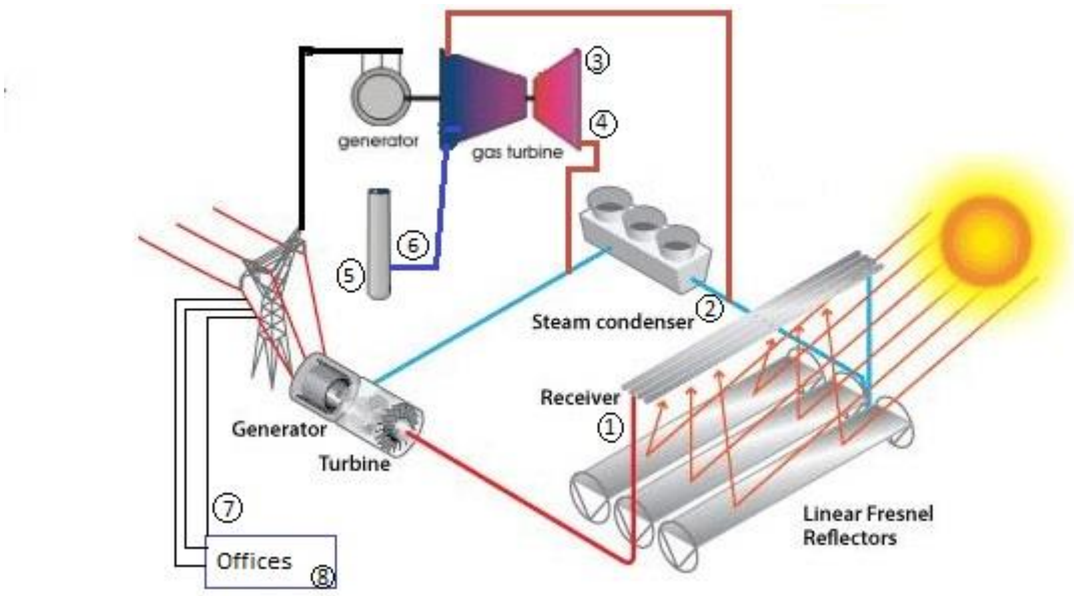

Figure 46: Measuring point in a Fresnel collectors CSP

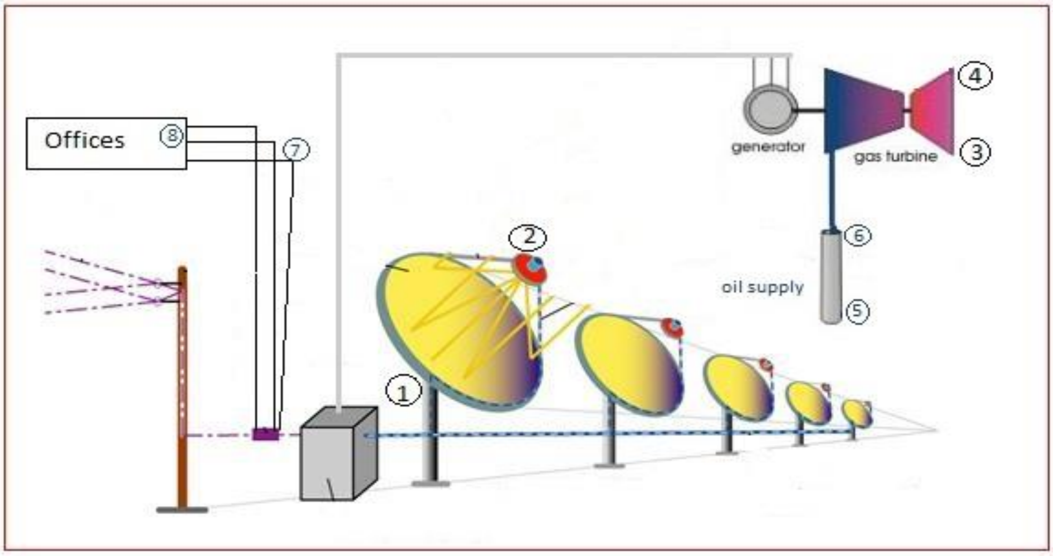

Figure 47: Measuring points in a solar dish CSP

6.2.4 Hybrid mode operation with battery storage

As mentioned in the previous sections, Hybrid mode operation of a CSP can be deployed by engaging a conventional fuel powered unit and can provide capacity credit factors, which in countries like Greece is an extra economic incentive for producers.

Hybrid mode operation of a CSP can also be achieved with the aid of electricity storage, such as a battery bank, as was shown in this thesis on Chapter 5. The proposed solution involves a lithium-ion battery bank that provides the energy needed in order to stabilize, enhance or extend the production of the CSP. The Greek code of non-interconnected islands includes measurements from other generation sets that are installed in the CSP but are not used in the payment method of the plant. If the hybrid mode of the CSP is deployed with a battery bank then the points and the structure of the solar dish CSP is displayed in Figure 48. The points that the Greek code requires measurements are at the dc-to-ac converter of the battery bank, before and after the converter at the power plant's connection point to the grid.

From the power grid operator perspective the measurements that required in this operational mode are about the energy that is stored or provided by the battery bank. The energy that is used by the battery bank can provide capacity credit factor to the power plant, as thoroughly discussed in Chapter 7. As already mentioned in Chapter 3, the capacity credit payment is an extra economic incentive to the producers so the power grid operator must be able to remunerate the capacity credit factor as efficient as possible.

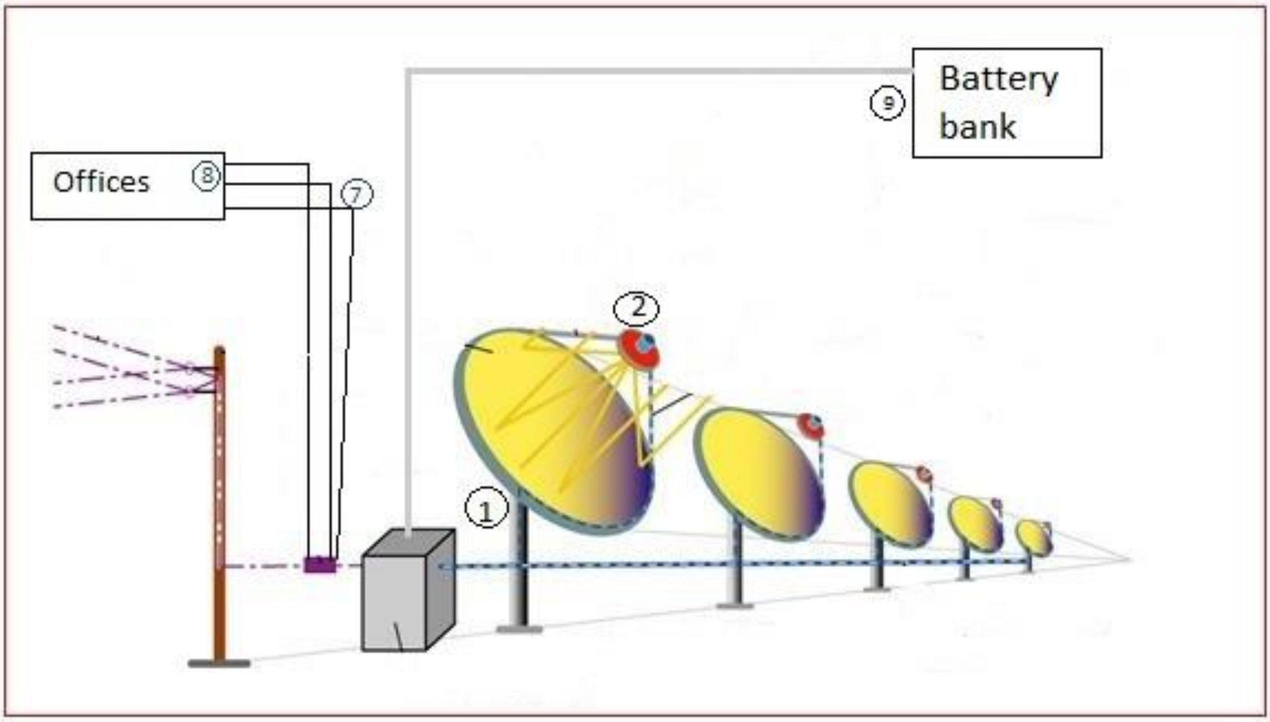

Figure 48: Solar dish with battery bank

This hybrid mode operation of the CSP power plant can provide capacity credit without any obligations from the regulations as for the energy usage of the plant. Also the renewable nature of the CSP is ensured as no conventional fuel is used in the power production process. For the power grid operator, measurements are an important task in this hybrid operational mode in order to determine the capacity credit factor and if it can be provided by the power plant.

7 Economic Evaluation

In Chapter 5 5 of this thesis a hybrid operation system, consisting of solar dish CSPs and a battery bank, was introduced. The proposed operation of this system can alleviate a lot of problems that RES units that depend on solar power face, like production instability and electricity production after sunshine. The question that should be answered not only for the potential investor but also for the regulators is how much this proposed operation should be remunerated.

Efficient management of batteries in island power systems with increased RES penetration can provide (in terms of adequacy in case of disturbance) both economic and operational benefits for both the power systems operators and the producers. Similarly, storage systems for islands based on the size of their energy systems have been proposed, suggesting that storage could even contribute to a cost reduction in electricity production in such power systems.[48]

One of the issues for storage systems is that they increase the already high cost of distributed and renewable energy sources, making them, mostly in market terms, even less economically viable.

However, it should not be overlooked that energy storage may provide even more benefits for power systems, which are difficult to be fully evaluated and accordingly remunerated. Indicatively, energy storage can help in local integration of solar energy, avoiding local upgrades of the distribution system or even contribute to facing power quality issues. [49]

To overcome financial barriers and create favorable market conditions for energy storage technologies, support schemes and policies must be developed. Feed-in tariffs, Green Certificates, tendering procedures, tax initiatives, and investment initiatives are examples of schemes that have been accepted by different governments and energy regulatory bodies, as shown on Chapter 3.

Currently, only Greece and Italy among EU countries have regulatory framework that supports installation of hybrid systems including energy storage and RES. Outside Europe, Algeria and South Africa are the ones that have specific regulation for energy storage, as shown on Chapter 3. All these countries, except Greece, have FIT systems, which differ a lot depending on the country. It is difficult to single out a FIT payment system from the other, because every country has different situations and particularities.

In the next paragraphs the Hybrid CSP system, which was proposed in Chapter 4, is going to be examined on the economic perspective.

7.1 Evaluation of CSP cost reduction

The first step to determine the appropriate FIT system is to evaluate the cost reduction that RES units provide to the power system. It is also important to evaluate the cost reduction of the proposed power plant in isolated grid systems. So in this paragraph the results of the CSP Hybrid unit simulation in Chapter 5 are used to determine the effect on the isolated grid of Crete, which is the study case in this paper. The main idea behind this simulation is to determine in what scale the CSP Hybrid Unit's operation affect the grid and what economic incentives are produced by this operation.

7.1.1 The algorithm used

In order to examine the economic impact of the CSP Hybrid unit, a load re-dispatch algorithm is going to be used. The operation of the algorithm is to simulate the cost of the units that are installed in Crete's power grid and by re-dispatch the load to find a better economic operation point taking into account the CSP injection. In order to simulate the economic operation of the grid, the fuel curves of the units are required. [50]

The algorithm works as described below. At first based on the units' fuel curves, the production reduction due to CSP Hybrid system production is optimally re-dispatched to the operating units of the power system at the period of simulation. No change in the unit commitment is expected. Thus, the most expensive unit or units reduce their output to accommodate for the production of the CSP plant and thus the maximum gain for the CSP hybrid mode is gained. Usually one unit, the most expensive one, decreases its production. If it can't, another unit should be selected based also on how expensive its operation is. It is important to note here that in the Cretan power grid the units that have the most expensive operation are the ones operating with diesel fuel. In Figure 49 the graphic representation of the algorithm's operation is displayed.

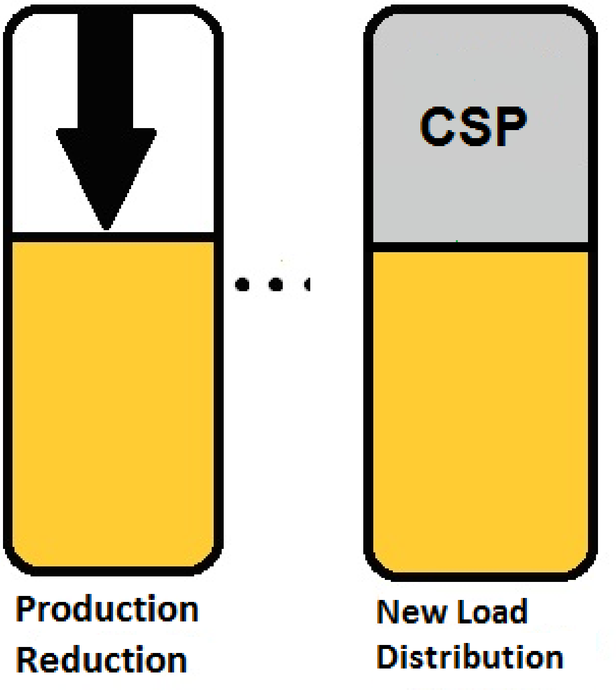

Figure 49: Re-dispatch algorithm

The main reason to use this algorithm is to test the economic impact that a possible re-dispatch of the unit's power production due to CSP power production has on the grid. In other words it is important to know the units that are going to reduce its production in order for the production of the CSP to fit in the load. The aforementioned is going to be the defining factor of the cost reduction of the power grid due to the CSP's power production and the corresponding calculations for the FiT proposed.

The algorithm aims to create a vector x that is the change in production that the units have. This vector is going to be subtracted from the initial thermal units' generation after the power reduction as shown in equation (36). This is the objective faction that the algorithm is based on.

$$F(x,t) = \min imise\left(\sum_{t=1}^{T} \sum_{i=1}^{gen\_\max\_num} f\left(dpg(i,t) - x(i,t)\right) \right) \quad (36)$$

But in order for the algorithm to operate in a close proximity to the real operation and also for the results to be logical some constraints need to be made. The constraints refer to every unit i and refer to their operational constraints such as technical minimum, ramp rates etc. These constraints are shown on equations (37)-(41). Equations (42) and (43) refer to the fact that there must always be some spinning reserve left in the system and that the demand must be always satisfied respectively.

$$Pg_i^{\min} \le dpg(i,t) - x(i,t) \quad (37)$$

$$dpg(i,t) - x(i,t) \le Pg_i^{\max} \quad (38)$$

$$dpg(i,t) - x(i,t) - dpg(i,t-1) + x(i,t-1) \le up\_rate_i \quad (39)$$

$$dpg(i,t-1) - x(i,t-1) - dpg(i,t) + x(i,t) \le down\_\mathrm{rate}_i \quad (40)$$

$$0 \le x(i,t) \tag{41}$$

$$\sum_{i \in IN} Pg_i^{\max} - \sum_{i \in IN} \left(dpg(i,t) - x(i,t) \right) \ge spin\_res(t) \tag{42}$$

$$\sum_{i \in IN} \left(dpg(i,t) - x(i,t) \right) = Demand(t) - CSP(t) \tag{43}$$

Where:

i : is a conventional unit on the island power system

t : is the time of the day

dpg_i : is the unit's production i before the introduction of the CSP.

Pg_i^{min} : is the technical minimum of the conventional unit i

Pg_i^{max} : is the technical maximum of the conventional unit i

up_rate_i : is how much the production of unit i can be increased within an hour

$down\_rate_i$: is how much the production of unit i can be lowered within an hour

Spin_res : is the spinning reserve of the power system

Demand : is the load to be covered by the thermal units at each period t

IN : is the set of committed units in Cretan power system

7.2 FIT design

In the previous paragraph, the methodology of evaluating economic benefits of the CSP Hybrid operation was presented. But only the economic benefits are not enough to determine the value of the CSP Hybrid operation. It is important for a mechanism to be established, for producers and also for grid operators, in order to give incentives in promoting and establishing this type of technology. Furthermore, it is important to remunerate the operation and the ancillary services that batteries provide to the grid.

Batteries have been considered as a means of providing support in power system dispatchers for a lot of years now, and have also been taken into account as models for providing spinning reserve and capacity credit. Their potential impact on power quality issues should be also acknowledged. They also enable the CSP to have more hours of production and more penetration, due to the extra energy provided. [51]

In general, two basic installations of storage systems exist, either storage installed as separate unit, as shown in Figure 49, or as part of a hybrid system, as shown in Figure 50. The installation in a hybrid system does not necessary mean that RES units (wind or photovoltaic or any other power plant) are physically installed at the same location as the storage unit. It could be just a conceptual combination of these two plants where each unit has its own grid connection but are operated as a single hybrid system. [49]

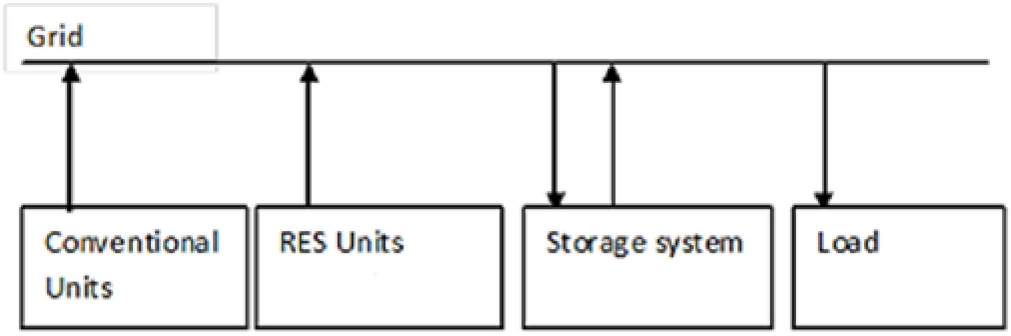

Figure 50: Storage system as separate unit

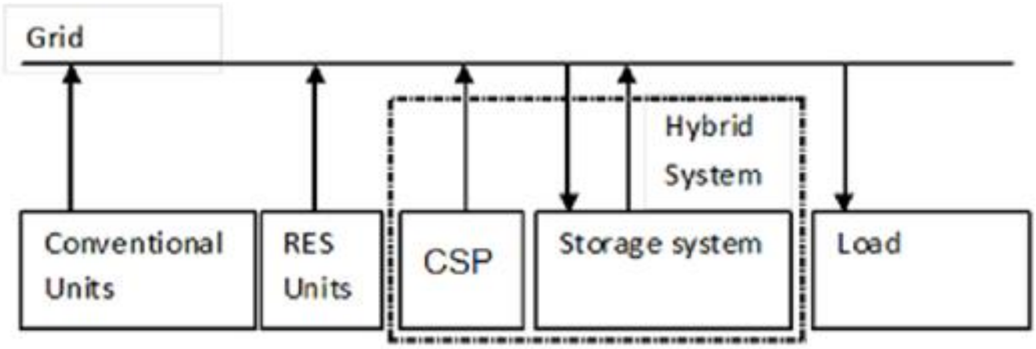

Figure 51: Storage system as part of a hybrid system

Each one of the presented concepts has its own advantages and field of application. The storage systems as separate units are mostly used in large power systems with numerous production units, hence the size of storage units is larger. Batteries are gaining popularity as the most common storage system due to their flexibility in capacity, and because they can be easier implemented in hybrid systems. Hybrid systems are more common on the islands and in standalone applications, as showcased in this thesis. Batteries are easier to implement in those in those applications because they require much less space for their installation, unlike pump-hydro (which is also site-specific) or thermal storage, and it is easier to measure their contribution, as shown in Chapter 6.

In this paragraph, emphasis is given on grid connected CSP-battery hybrid operation system in autonomous power systems, like the island of Crete that is used in this thesis. Even more focus is given on evaluating FIT scheme for capacity credit purposes. There are a lot of parameters that should be taken into account in designing a FIT system. The parameters possibly affecting operation of the proposed system and which should be taken into account when designing FIT for batteries are the following:

The Storage capacity in terms of kWh (*BatCap*): The storage value varies depending on the storage capacity. Even low values may provide aid in supporting the power system, whereas in some cases increasing storage capacity may even lead to very limited additional benefits. This will also be discussed in the case study. There should be additional incentives to balance batteries and CSP capacity so that the benefits for the power system, especially in terms of fuel consumption, avoidance of emissions and capacity credit, are increased as much as possible.

Capacity Credit (*CapCre*). This is closely related to *BatCap*, since these two parameters should correlate. The amount of capacity that the system can provide must be discussed and accordingly remunerated. It seems logical that the higher the capacity credit of the system the more benefits it will produce, but in isolated island grids like the Cretan one, the swift in energy injection may result in more expensive power production.

The Fuel price (*FuelPrice*). When the units affected are identical and consume the same type of fuel, such an evaluation is much easier than for multi-fueled power systems. Changes in fuel prices should somehow be reflected on the FIT value, because the fuel price also reflects the real value of the RES technology. This will draw investors to power systems where fuel savings are greater. Investors might also endeavor to optimize production during hours when fuel benefits are higher, i.e. when more expensive units are expected to operate. However, caution should be taken so that FIT is not very sensitive to fuel price because fuel price fluctuation may create uncertainty in investors and have the opposite result.

Therefore, the mathematical formula for the FIT, apart from the considerations on the payback period and improved IRR, should take the above considerations into account like equation (43).

$$FIT = function\left(BatCap, CapCre, FuelPrice\right) \qquad (43)$$

As the cost reduction is highly depended on the fuel price, especially in isolated grids, it is important to establish the value of the fuel reduction that is happening due to the proposed operation. Also in most cases in FIT structure around the world, the proposed FIT is depended only on fuel price, due to the cost reduction accounted to RES units. In equation (44) the proposed correlation between the FIT price and fuel price is presented.

$$FIT\left(FP\right) = FIT \cdot \left\{0.90 + \frac{0.10 \cdot FP}{0.9899}\right\} \qquad (44)$$

where:

FIT : is the Feed-in Tariff price

FP : is the Fuel Price

Here it is important to note that 0.9 is the percentage that is not going to affect the FIT for the CSP Hybrid unit. The 0.1 percentage is selected in order to reflect the fuel cost to the power grid. Also 0.9899 is the base fuel price in €/lt of diesel fuel, as seen in the Cretan power system, which is going to be saved. The diesel fuel price is selected in this formula because after running simulations with lower fuel prices, the economic benefits of the power grid were proportional to the diesel fuel price. So the simulations showed that the economics of the power grid are sensitive in changes in the diesel fuel's price.

Additional analysis is needed to determine the value of capacity credit of the various combinations studied. Increasing the capacity credit, especially after sunset, helps the power grid operator to increase adequacy of the power system delay or even postpone a more expensive unit commitment. This reduces uncertainty for the power system operators and under circumstances can even lead to avoidance or postponement of committing additional operating unit, thus reducing the duck curve effect, as shown in Chapter 4.2. Additionally helps in increasing the operational hours of the CSP around and after sunset.

The remuneration of capacity credit on annual basis takes the form of providing a service, and it is based on *CapCre* values and the fuel savings achieved during the operation. The difference between the savings in fuel and the CSP remuneration is used as the basis for calculating suggested tariff schemes for batteries at various penetration levels. It is important to note here that the suggested scheme is going to be a premium FiT for producers that provide hour to hour utility services to the grid.

7.3 Results

The algorithm, which is described in paragraph 7.1, is a great tool to determine the cost reduction evaluation that the CSP Hybrid unit is providing to the Crete's power grid. But it is also important to determine the value of the capacity credit, as discussed in Chapters 3 and 5. In order to do that it is important to estimate the value of the components of the CSP Hybrid unit, which are the solar disks and the battery bank.

It is important to note here that in Greece there is regulation about capacity credit but the remuneration occurs in yearly basis. Also in this scheme the benefits for the producers are higher if they reach 100% of nominal power as capacity credit, which in most RES cases is difficult to accomplish, and is remunerated in 35.000 €/MW per year if the criteria that are described in Chapter 6 are fulfilled. There is also a scheme that compensates RES unit power producers that also provide utility services, especially in isolated grids like the Cretan one. The scheme acts as a premium FIT and the remuneration of the production is 20 €/MWh, if the plant can provide 100% of its capacity for two hours after sunset.

In this section the proposed scheme is about partial capacity credit on a daily basis. The scheme presented here is more flexible for the power producers, provides daily assurances to power grid operators, benefits to the producers and makes easier to implement RES power production units.[52]

The first scenario as presented before, and as described in Chapter 5, is a CSP solar disk park operating as usual without any aid from a storage facility.

In the second scenario alongside the CSP a battery bank is implemented so as to provide capacity credit after sunshine and partial production stabilization.

The third scenario the objective of the system is to provide production stabilization and capacity credit, with the difference from the second scenario that the battery bank capacity has been doubled and provides double capacity credit for the same hours.

These three scenarios are enough to determine the value of the CSP Hybrid system and also the value of capacity credit for the system. The simulation with higher capacity credit is used to determine if higher capacity after sunset is more beneficial to the grid than simply injecting CSP into the grid. The value of capacity is critical in isolated grids because maybe there is not enough electrical space in the energy mix to integrate the CSP Hybrid system power production.

Thus the following, three scenarios were selected to be simulated:

- CSP operation with no battery
- CSP operation with battery bank and capacity of 150 kW two hours after sunset, 15% of CSP nominal power
- CSP operation with battery bank and capacity of 300 kW two hours after sunset, 30% of CSP nominal power

The aforementioned simulations, have resulted, as expected, in reducing the operational cost of the Crete's power grid. It is important to note here that the scenario with the double battery size and double the capacity credit is expected to have the most benefit, while the other two are expected to have close benefits to it as well. The results that the scenarios provide, running the scenarios in different times of the year, are shown on Table 20.

The scenarios are based in running the algorithm that was described in the previous paragraph and in the 'duck curve' effect reduction algorithm described in Chapter 5.2.

The results are obtained by examining 10 days throughout the year 2 of each season with two winter days to have a better understanding of the season. So there are 2 successive days in winter (2 days from different areas of this season), spring, summer and autumn are selected and the data and results of these days are examined. These days are a great example of the season they represent and also with using the next day also, not only the battery bank impact is examined but also, the stability of the algorithm was tested in order to satisfy the grid's requirements. Also the back to back days were selected in order to check if the capacity of the battery is enough to provide the utilities discussed above and also if the algorithm can operate with the energy that is left to the batteries from the day before.

Table 20: Simulation economic results

Simulation	**Benefit €/10days**	**Benefit €/MWh**	**Total Production MWh**
CSP with no batteries	8460.54	238.19	35.52
CSP capacity 150 kW	8441.79	238.51	35.40
CSP capacity 300 kW	8604.65	238.75	36.04

From the above table it is clear that the higher cost reduction is provided with the CSP Hybrid system with the largest battery system and the highest capacity. Also the CSP hybrid system with 150 kW capacity credit has the lowest economic benefit, which can be explained because the available energy is used also to stabilize the CSP's power production, but the economic benefits per MWh are increasing because of this enhanced operation.

It is also important to note that the open cycle gas-turbine operation is affected. This is expected since these units are the most expensive ones in the Cretan power system also due to high prices of diesel fuel against HFO fuel which has almost half the price. Also it is logical that the benefits will be much higher when the capacity of the CSP Hybrid system, meaning both the CSP and the battery capacity, is increased.

These results provide much information that can help regulators and all parties involved to determine how to remunerate the capacity credit.

7.3.1 Suggested Remuneration scheme

As discussed in paragraph 7.2, capacity credit provides services to the grid, but cannot be increased to the level that the producer wants. As in this case the producer can increase the capacity credit up to 100%, which until now is remunerated as a service provision per year.

However, if daily production of CSP is remunerated under FIT scheme per day, or per hour, the whole payment system of a CSP Hybrid operation as the one suggested in this thesis which also provides capacity credit would have been complicated. This means that the payment system is a mix of FIT and capacity payment that happen in different periods of time. There are additional benefits that can be exploited if the remuneration method in the capacity credit mechanism changes on a yearly basis compared to daily one.

It is important in order to presented the suggested remuneration scheme, to calculate the difference between the economic benefits as presented in Table 20 and the benefits if the injected power from the CSP plant is remunerated at the calculated tariff of No storage case, I.e. 238.19€/MWh. This difference is presented in Table 21 for 10 days and up-scaled for 1 year.

Table 21: Comparison in benefits

Simulation	Remuneration **€/10days**	**Difference €/10 days**	**Estimated Difference 1 year**
CSP capacity 150 kW	8430.595	11.193	408.556
CSP capacity 300 kW	8584.273	20.381	743.910

The estimated difference in value of CSP Hybrid plant should be retrieved by the premium FIT values.

The corresponding values expressed in terms of *CapCre* for various values of Capacity are summarized with the formulas of Table 22.

Table 22: Remuneration scheme for capacity credit

Capacity Credit kW	**Remuneration €**
<150	$2.72 \cdot CapCre$
150 - 300	$\frac{2.72 \cdot lmt(1) + 2.236 \cdot \left(CapCre - lmt(1)\right)}{CapCre}$

In the above table *CapCre* is the Capacity Credit that the system can reach in any time and *lmt* is the limit if the previous section of that scheme. The constant values in these formulas are calculated based on the difference between flat economic benefits and benefits bases on per kWh payment.

It is logical to assume that the power system benefits increase as the CSP capacity increases. However the battery capacity increase depends on the stabilization algorithm and the amount of capacity credit that the producer wants to provide to the grid. From the above table it is clear that the economic benefits for the power grid increase with the amount of capacity credit, but not in a way that compromises the grid stability.

This scheme, compared to the one described in Chapter 3, is straighter forward towards the remuneration of capacity credit and is rewarding the producer for utility services daily. This can lead to investors lead more towards the capacity mechanism, thus creating more advanced CSP power plants, which have more stable production and can provide more utility services to the power grid. The fuel price influence in the economic parameters is shown in equation 44, with the premium remuneration of the FIT included.

8 Conclusion

In this thesis the main focus, as shown on previous paragraphs, was to examine CSP technologies outside the scope of injecting electricity during sunshine hours only. In places with favorable solar conditions, CSPs have more advantages than other RES units, wind turbines and PVs, like more stable production, larger amount of production in smaller installation area and with the proper addition of storage the ability to provide utility services to the grid and maybe in the future to replace conventional fuel powered base load units. Due to these characteristics, CSPs are gaining popularity mainly in countries that have high solar radiation levels, like countries in the MENA region and South Europe.

There are 4 main different CSP technologies, as described in Chapter 2, which are currently implemented in power plants around the world. Most of these CSP installations aim in large-scale electricity production. Also in many of these installations, the implemented CSPs production is aided by a conventional fuel powered unit or a storage unit, which enables the CSP to also provide utility services and have stable production to be considered as base load unit. Apart from base units, some CSPs have also the ability for smaller, easier integrated power production. Especially solar dish CSP technology is easier to integrate in such grids due to its characteristics. The characteristics that make solar dish CSPs more flexible are its relative small size, the fact that each unit has independent production and they can be easier combined with battery electricity storage such flexibility is crucial for CSP integration in smaller, isolated grids, like the Cretan one that is showcased in this thesis.

It is also important to draw conclusions from the regulations of other countries, which also have high solar radiation, such as Greece and have regulations to promote the installation of CSP power plants, as reviewed on Chapter 3. A new trend in regulation is that CSP units are not only remunerated for their power production, but also for the utility services that they can provide. Also a lot of countries, in order to enable their CSP power plants to provide these utility services, have regulations to promote this kind of operation. Furthermore, depending on the country power production aid from external sources, like conventional fuel powered units, biomass powered units and storage both thermal and electrical (batteries) is promoted. This type of regulations promotes the installation of state of the art CSPs that have more stable output and also can provide capacity credit to the power grid. However, Greece is the only country that gives incentives to producers who provide capacity credit to the system, mainly because of grid stabilization reasons due to the fact that isolated island grids have high RES penetration but not stable enough production to cover the load efficiently. Also due to high solar RES units' penetration, grids have stability issues after sunset, a problem called the 'duck curve' effect, which is thoroughly explained in Chapter 4. Two examples of "duck effect" on the island of Crete also are presented showing its magnitude, which can lead to covering in two hours a gap in the load up to 60 MW in winter and 100MW in summer.

In the scope that is discussed above, if CSPs solve the main problems that they have, production instability and the 'duck curve' effect then they will also have the ability to act as conventional powered units and gradually replace them. The selected CSP in this thesis to examine the extent this is possible, is a 1 MW solar park comprising of CSP solar dishes assumed to be installed in the isolated grid of the Crete Island in Greece. Crete Island was selected because it is an isolated grid with high solar radiation while not enough electrical space for new RES units to be installed exists. In Crete there is interest in investing for CSP units that have large output, but before the island's interconnection to the mainland such projects do not seem possible to be completed. So the value of a hybrid CSP-battery bank plant to either smooth CSP injection to the grid during sunshine periods or to provide extension of production outside sunshine hours has to be investigated for achieving easier integration of the CSP Hybrid unit into such Grids.

First of all, as was described on Chapter 5, the mathematical model that simulates the operation of the solar dish Stirling CSP is presented. First of all, the model of the solar dish is based on formulas that describe the operation of each one of the three major components, namely the solar collector, the thermal receiver and the Stirling engine.

Also modeling of the solar geometry has been done in order to achieve the maximum collection efficiency of thermal energy from the sun. So after modeling the solar geometry in order to achieve optimal positioning, modeling of the parabolic collector is imminent in order to calculate the amount of thermal energy that is collected from the sun. The thermal energy that is collected is driven to the thermal receiver, which uses the energy as an input to the Stirling engine. The process to model the thermal receiver is based on calculating the thermal losses that this CSP component has, in order to find out the energy that finally powers the Stirling engine. The output of the Stirling engine, which is the total power output of the solar dish CSP, is calculated based on the mean efficiency factor that Stirling engines have, based on bibliography.

By modeling the behavior of all of these components, a simulation of the operation of a CSP solar dish can take place. In the logistic model, which is thoroughly described in Chapter 5, the only input is the weather conditions, namely direct normal solar radiation and temperature. These conditions can be easily obtained by any weather agency in the world at no or very small cost. So by having an operational model of the CSP, it is easy by inserting the weather input to determine the power production. In order to determine the power output of the whole plant a logistic model of a Li-ion battery bank was also developed. The battery bank model is based on the operating states of the battery and the power exchanged. By having the operational models of all the part comprising the CSP it is easier to schedule the production of the plant to tackle with the problems of either production instability or 'duck curve' effect or both of them.

In order to face these two problems, two algorithms were developed. The first one, after taking into account all the physical constraints that the equipment has, develops an operation schedule in order to reduce hour-to-hour differences, peak-to-peak differences and to provide capacity credit to the grid during the operational hours of the plant. The algorithm computes the mean square error of the production without stabilization and compares it to the production of the perfect stabilized power production. So the new operation of the CSP is based on reducing the mean square error between these two operations, regarding the physical constraints of the parts comprising the power plant and the battery. The second algorithm is about providing capacity credit beyond the hours of sunshine. The algorithm takes into account the amount that the producer would like to provide after sunset for a specific period and the rest of the energy that remains in the battery bank is used to partly stabilize the production of the plant.

Power production volatility and 'duck curve' reduction has many advantages for all involved stakeholders, including the producers and the operator of the island. First of all, regarding the volatility reduction, reducing at the same time the uncertainty of such sources, power grid operators are able to include solar dish-Stirling units more easily and frequently in the power production schedule of the grid. Also the 'duck curve' effect reduction makes the CSP more reliable and also provides the necessary time to the power grid operator to replace the CSP production with production from conventional fuel powered units, leading to more efficient decisions in economic scheduling functions. The owner of the Hybrid plant can provide capacity credit to the power system, which can be additionally remunerated as described in the Non-Interconnected Islands Grid Code of Greece.

In our case study, a battery bank with 700 kW and 705 kWh was considered. The application of the proposed algorithms had as effect:

- Reducing volatility of CSP output by an average mean square error reduction of 73% and an average peak-to-peak difference reduction in generation of the CSP of 54.6%
- Electricity production after two hours after sunset with production of 15% and 30% of the nominal output of the plant is feasible
- Capacity credit throughout the day and for two hours after production of power of 15% and 30% of the nominal output of the plant is also feasible
- More reliable electricity production, through less dependence in solar radiation and easier economic scheduling of the grid

By utilizing storage, a CSP unit is enabled to also provide utility services, like capacity credit as extensively discussed in this thesis. So there is a question raised of how the power grid operators and the agencies that are responsible for remuneration of electricity are going to certify that the producer is providing capacity credit and if and to what extent the capacity credit is provided only by renewable energy. The solution to this is to impose via Grid Codes the producers to install measuring units to their CSPs, in order to provide information not only for the power grid operators and the most efficient management of the grid but also for the remuneration of the production to be accurate and acceptable by both parties. There are regulations both in Greece and abroad about monitoring CSP facilities but only in Greece regulation these points towards remunerating capacity credit are fully described. As described in Chapter 6, in Greece capacity credit can be provided with the aid of either conventional or biomass fuel powered unit, but limited up to 20% of the overall power production of the plant. So measurements are important for both the producer, to establish whether or not the CSP can provide capacity credit and for the power grid operator, to verify whether the capacity requirements have been reached according to regulations.

Capacity credit is a utility service that nowadays, as shown in this thesis, is achievable and thus the power grid operators should try to request and promote for RES units. Greece is the country that this concept first appeared, but the capacity credit is only remunerated if the capacity is at 100% of the plant's nominal power. In Chapter 7, a methodology to evaluate capacity credit value at a percentage of the nominal capacity for hours beyond the sunshine hours is presented. This new scheme is about remunerating the capacity credit on a daily basis and also remunerates any capacity level that the producer can provide not only 100% of the plant's nominal power. This methodology calculates the expected fuel savings in grid operation when a Hybrid CSP plant operates providing extended duration of CSP operation at specific output compared to CSP only benefits. Thus a fair enough FIT system can be proposed reflecting the savings achieved.

This methodology is based on a Sequential Quadratic programming optimization algorithm that evaluates the maximum savings due to CSP injection to the grid by re-dispatching demand to the committed units of the power system. The developed algorithm takes into account the fuel consumption curves and the technical characteristics of the Power System Units. Basically the algorithm selects the units with the most expensive production, usually a gas turbine or a diesel unit for the Cretan power System, lowers their production so as to create electrical space for the CSP with the highest economic benefits from the CSP Hybrid operation.

However, if daily production of CSP is remunerated under FIT scheme per day, or per hour, the whole payment system of a CSP Hybrid operation as the one suggested in this thesis which also provides capacity credit would have been complicated. This means that a new FiT scheme must be introduced that takes capacity credit into account daily and also changes depending on the amount of the capacity credit that the producer can provide. There are additional benefits that can be exploited if the remuneration method in the capacity credit mechanism changes from a yearly basis compared to daily one. Furthermore, the new FiT should depend on the battery capacity, the capacity credit provided and partially of the fuel price that the most expensive units of the grid use, so as to depict more precisely the economic impact of the Hybrid CSP to the power system.

Simulations of Operation of the power grid have taken place in order to establish if there are economic benefits of the operation proposed in Chapter 5 compared to CSP only operation. The simulations are based on real data of the Cretan grid operation for characteristic successive days, from each season of the year, as selected as described in Chapter 5. The economic benefits determine the proposed FiT scheme, which is based on the battery capacity, capacity credit and the fuel price of the conventional units affected. The scheme is an additional premium FiT that remunerates the capacity credit provided in terms of €/ kWh in addition to the power production FiT that the producer may already have. The scheme is more detailed explained in Chapter 7.

From this thesis a lot of conclusions can be drawn. The first one is that the two main problems of CSPs, which are power production volatility and ‘duck curve’ effect, can be tackled effectively with the addition of storage, even in smaller scales like the CSP and also in isolated grids, if algorithms like the ones described above and showcased in this thesis are applied in the grid’s operation. By tackling with such issues the CSP plants are enabled to provide production as stable as conventional fuel powered units and also provide utility services to the grid, like capacity credit. Additionally the operation of the CSP units becomes more flexible thus enabling the producer to have multiple different operations and more profits. Furthermore with regulation that promotes state of the art RES units a future with eco-friendly electricity production is possible. Also measuring requirements should be updated in order to enable the power grid operator to engage more CSP units and also to verify the capacity credit.

As described above, considerable reduction of production volatility and ‘duck curve’ effect reduction is achievable with relatively low capacity batteries. Thus, the electricity production from RES units should be accompanied by a storage unit of any kind, as this helps mitigating the major disadvantage of RES units, of production volatility and ‘duck curve’ effect. All these actions result to gradually replacing conventional units by RES making the power generation in power systems, especially in island power grids, as eco-friendly as possible and thus the customers and visitors more satisfied. All the above have been described thoroughly on Chapter 5.

Modeling of other solar-hybrid technologies providing specific values of capacity credit for certain periods can be a future extension of this thesis. Especially if CSP is to be used, thermal storage modeling, which enhances the production alongside the solar thermal cycle, should be accordingly modeled so as similar operating results can be achieved. The thermal enhancement can be also possible with the aid of a conventional fuel powered unit, with the difference compared to the thermal storage to be more dispatchable and not renewable. In such a case, the value of hybrid CSP-Conventional operation at various CSP shares should be able to be remunerated so that the CSP technology can be combined either with existing conventional units to improve their environmental performance or with future installed units. Furthermore it is also important to examine also the amount of stability and capacity credit that can be provided and whether these types of operation are more beneficial to the producers than simply electricity production during sunshine time and injection to the Grid.

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