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UNIVERSIDAD PONTIFICIA

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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

COMPARATIVE ANALYSIS OF THE SOLAR ENERGY ROLE IN THE SUPPLY OF ELECTRICITY IN SPAIN AND CALIFORNIA

Autor: Michel Maria Garcia

Director: George Gross

Madrid

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Comparative analysis of the solar energy role in the supply of electricity in Spain and California

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Finally, this list would be incomplete without thanking the most important thing, my family, for their unbelievable and unconditional support and love throughout the years.

ANÁLISIS COMPARATIVO DEL ROL DE LA ENERGIA SOLAR EN EL SUMINISTRO DE ELECTRICIDAD EN ESPAÑA Y CALIFORNIA

Autor: Maria Garcia, Michel.

Director: Gross, George.

Entidad Colaboradora: University of Illinois at Urbana-Champaign.

RESUMEN EJECUTIVO DEL PROYECTO

1. INTRODUCCIÓN

Existe una preocupación generalizada sobre la necesidad de reducir las cantidades de emisiones de CO_2 que se emiten cada año para combatir de manera efectiva los impactos del cambio climático.La industria de la energía eléctrica desempeña un papel clave en todo el mundo, ya que debe ser fiable y eficiente para satisfacer todas las necesidades de energía de todos los que están conectados a la red, pero al mismo tiempo, la industria de la energía eléctrica debe contribuir en la reducción de emisiones de gases de efecto invernadero. Para conseguir este objetivo, la progresiva introducción de fuentes de energía renovable en sustitución de fuentes de energía basadas en combustibles fósiles es clave. Dentro del amplio espectro de opciones en cuanto a fuentes de energía renovable, la energía solar se encuentra como una opción puntera, debido al gran desarrollo en términos de eficiencia combinado con una gran reducción en los costes de producción durante los últimos años. Este proyecto pretende realizar un análisis de como la energía solar en sus dos vertientes principales, solar fotovoltaica y solar térmica de concentración, ha evolucionado en dos territorios clave dentro de su contexto geográfico, como es California dentro de los Estados Unidos de América y España dentro de Europa. Estos dos territorios se encuentran entre los primeros que adoptaron tecnologías solares y se han situado al frente de su desarrollo. A lo largo de la realización de este proyecto, se determinarán las diferencias existentes en la introducción de este tipo de tecnologías en la red en el periodo estudiado comprendido entre los años 2008 y 2018 y como el nivel de eficiencia en términos del factor de capacitancia se ha desarrollado

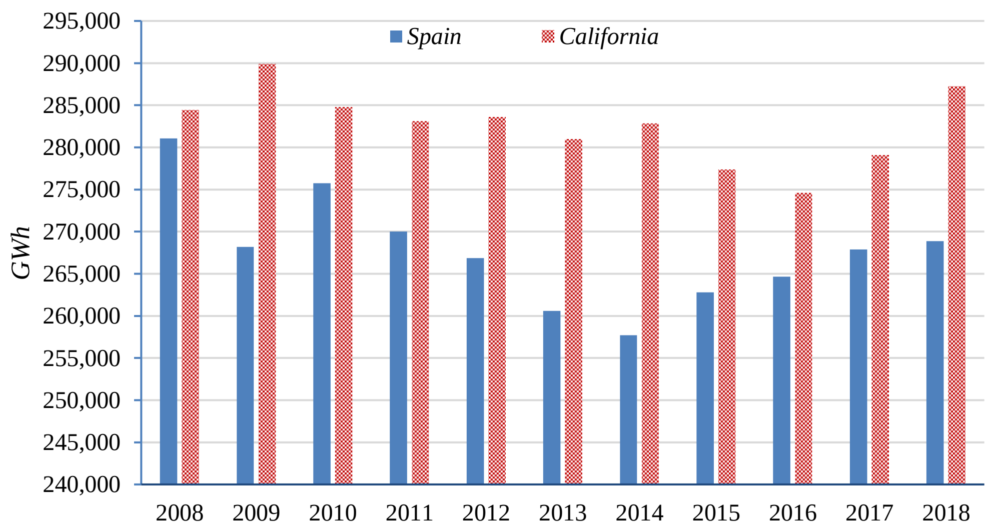
durante esos años. Para eso, se estudiarán las características principales de los sistemas eléctricos de ambas regiones, la demanda, la generación eléctrica, el rol de las energías renovables entre otras variables. Se realizarán además un estudio de las emisiones de CO_2 evitadas debido a la generación de electricidad mediante energía solar y un estudio de las diferencias del *LCOE* de una planta fotovoltaica entre una región y otra.

2. RESUMEN DE LAS REGIONES DE CALIFORNIA Y ESPAÑA

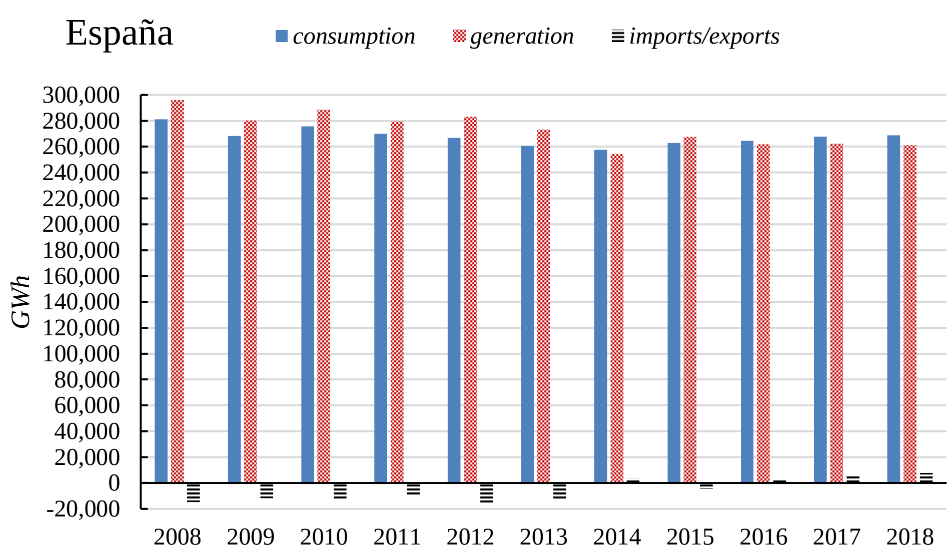
La comparación entre estos dos territorios es interesante porque presentan muchas similitudes a nivel geográfico y demográfico, siendo la diferencia más notable el producto interior bruto, mucho mayor en California.

En cuanto al sistema eléctrico, ambos territorios presentan picos de demanda anuales muy similares, siendo en el año 2018 de 40,947 *MW* en España y de 46,427 *MW* en California. A su vez, estos valores se encuentran lejos del récord de pico de demanda en ambas regiones, que se alcanzó en 2007 en España y en 2006 en California, teniendo una variación similar de -11 % respecto a ese récord del pico de demanda en el año 2018.

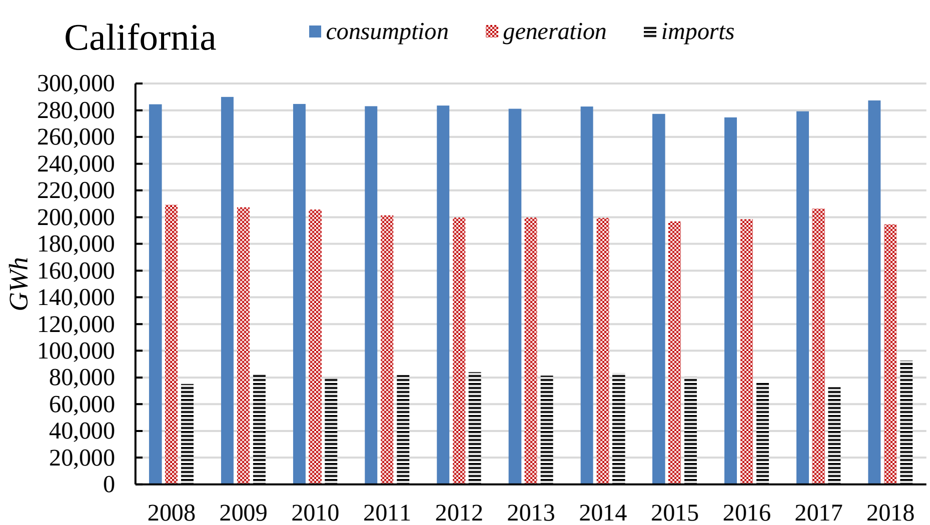
El consumo anual de electricidad es muy similar durante el periodo estudiado, como se puede apreciar en la siguiente gráfica.



En cambio, cuando comparamos la generación frente al consumo eléctrico de ambos territorios, las diferencias son claras. España tiene una generación muy similar al consumo eléctrico anual, lo que origina importaciones/exportaciones de electricidad de valores muy pequeños.

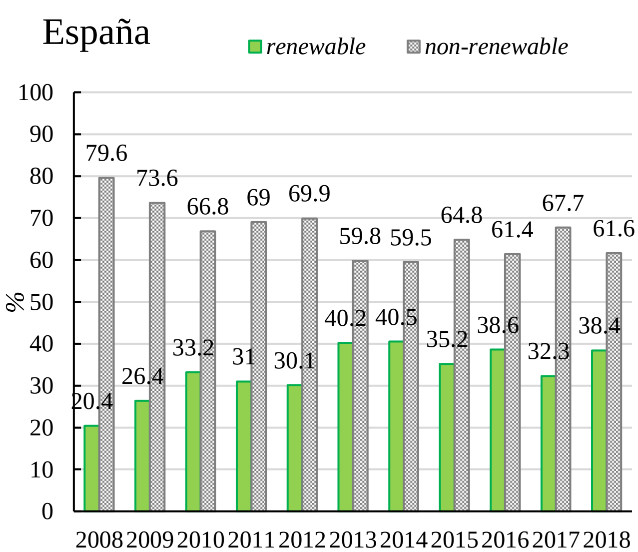


En cambio, como se puede observar en la siguiente gráfica, California depende en gran cantidad de importaciones de estados vecinos como Oregón, Nevada o Arizona para satisfacer su demanda anual de electricidad, cubriendo la generación de electricidad dentro del estado aproximadamente dos tercios de la demanda anual.

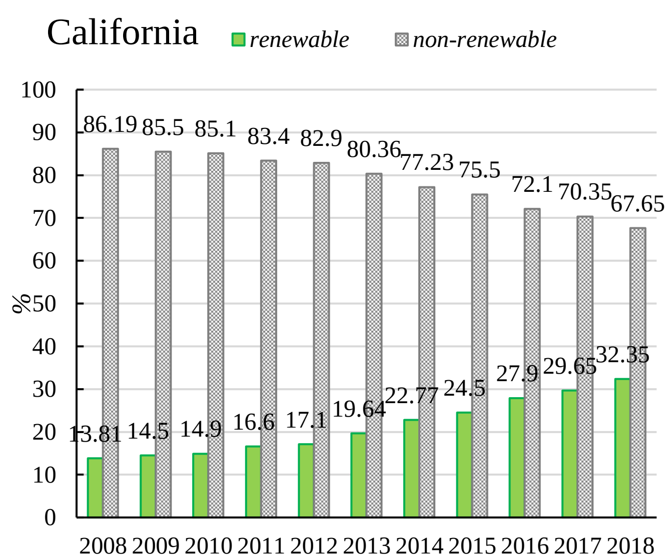


Comparando las redes eléctricas de ambos territorios se pueden observar grandes diferencias a simple vista. La red eléctrica de España presenta una mayor variedad de tecnologías que contribuyen a la generación de electricidad, con una gran presencia de renovables. En cambio, la red eléctrica de California depende en gran medida de 2 tecnologías: gas natural e hidroeléctrica, con una gran presencia a partir de 2015 de la energía solar fotovoltaica. Comparando las gráficas de generación y capacidad instalada de ambos países se aprecia una clara tendencia a disminuir la generación año tras año, cuando cada vez la capacidad instalada a la red eléctrica es mayor. Esto es debido a la progresiva inclusión de energías renovables.

Por último, se pueden observar en las dos gráficas siguientes la evolución de presencia renovable dentro de la generación eléctrica, con España manteniéndose por encima del 30 % de generación renovable desde 2010, con un pico del 40.5 % en 2014, y con California en clara ascensión debido a la gran inversión en solar fotovoltaica principalmente, superando por primera vez el umbral del 30 % en 2018.



(Renewable include hydro, hydropower, wind, solar PV and CSP, other renewables and renewable waste)

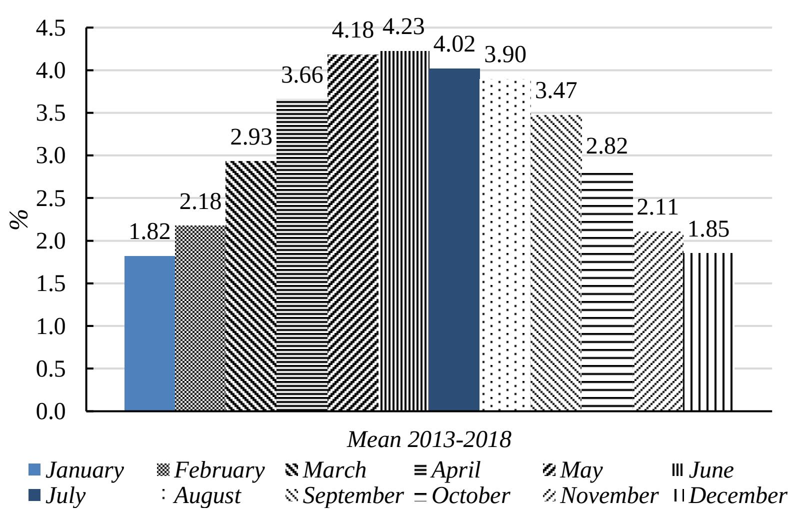


(Renewable include hydro, solar PV and CSP, wind, biomass and geothermal)

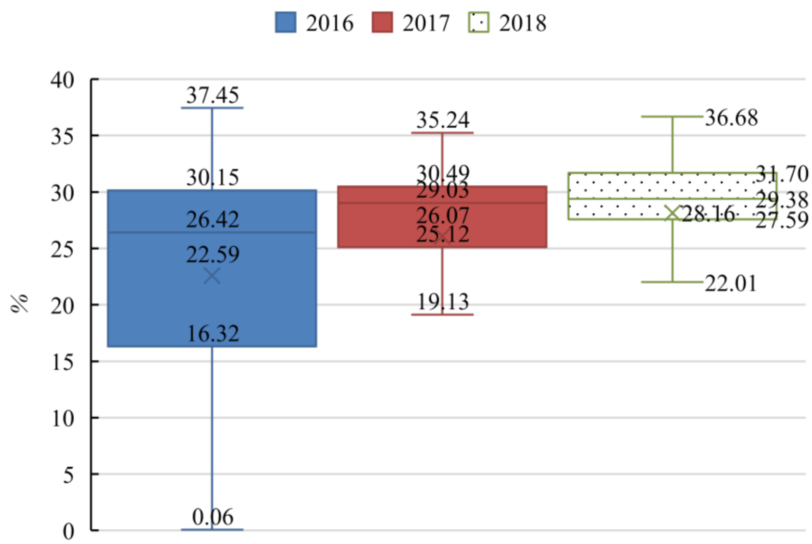
3. ANÁLISIS COMPARATIVO DE LOS RECURSOS SOLARES EN CALIFORNIA Y ESPAÑA

La irradiación solar es un apartado clave para el funcionamiento y rendimiento de la energía solar fotovoltaica y la energía solar térmica de concentración. Comparando las principales zonas donde se construyen plantas fotovoltaicas y térmicas de concentración en España y California, se aprecia una irradiación media mayor en California, por lo que el rendimiento esperado allí será mayor que el de España, como se verá en el proyecto. La energía solar fotovoltaica ha seguido caminos diferentes en ambos territorios. En España, la capacidad instalada se encuentra en torno a los 4,600-4,700 *MW* desde 2013, mientras que, en California, la progresión es ascendente desde 2008, llegando a superar los 10,000 *MW* de potencia instalada en 2018. En cuanto al factor de capacidad de la energía solar fotovoltaica, también se aprecian diferencias, este apenas llegando al 20 % en España, mientras que en California este valor asciende hasta incluso el 26 %.

En este proyecto se han desarrollado distintos análisis como los mostrados a continuación. La siguiente gráfica muestra el porcentaje mensual respecto al total de la generación de electricidad de la energía solar fotovoltaica en España. Se puede observar como desde 2013 hasta 2018, en los meses de verano, más de un 4 % de la generación es fotovoltaica, valor que desciende a menos del 2 % en meses de invierno.

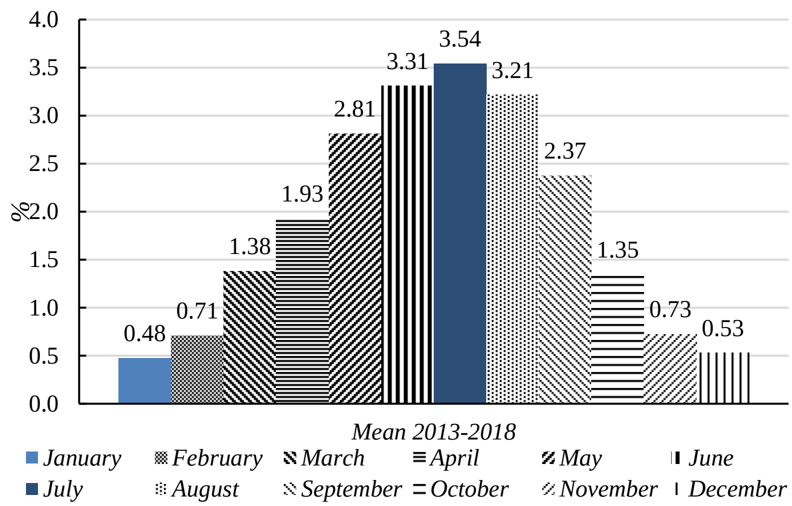


En el caso de California hemos analizado el rendimiento de todas las plantas fotovoltaicas con una potencia mayor de 20 *MW*, debido al gran número de estas comparado con España. Se puede apreciar como en el diagrama de cajas como el rendimiento mejora año a año ha medida que la energía solar fotovoltaica se afianza y madura como tecnología.

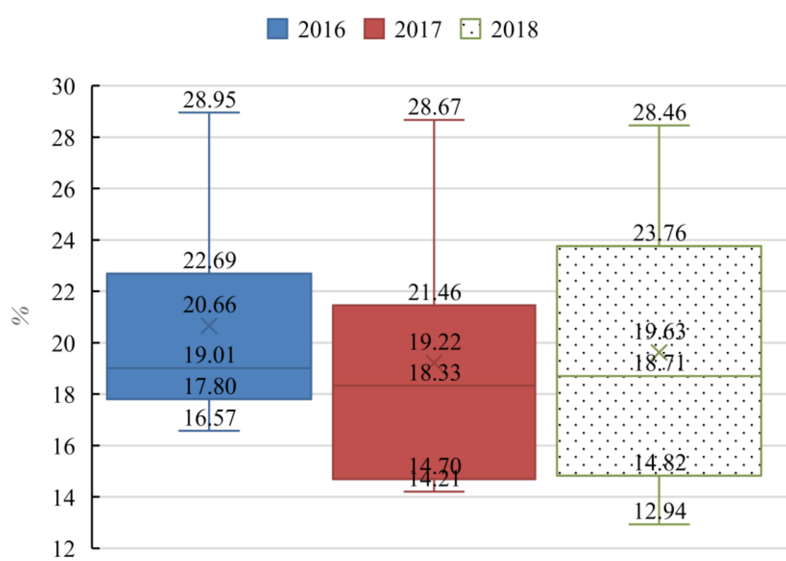


En el caso de la energía solar térmica de concentración, existe una cierta similitud respecto al desarrollo en ambas regiones. Las primeras plantas de cilindro parabólico (Solar Electric Generating Stations) fueron construidas a mediados de los ochenta en California, mientras que España fue el primer país de Europa en adoptar este tipo de tecnología en 2008. Ambas regiones son pioneras respecto al desarrollo de esta tecnología en todo el mundo. Incluso la inversión en esta tecnología se "detuvo" prácticamente al mismo tiempo, ya que en España no existen conexiones de nuevas plantas a la red desde 2013, mientras que en California es desde 2014, cuando se inauguraron 3 grandes proyectos.

La siguiente gráfica muestra el porcentaje mensual respecto a la generación total que la energía solar térmica de concentración proporciona en España. Como se puede observar, desde 2013 hasta 2018, en meses de verano, el porcentaje de producción llega incluso a sobrepasar el 3.5 % del total de la generación, valor que desciende drásticamente hasta menos de un 0.5 % en el mes de enero.

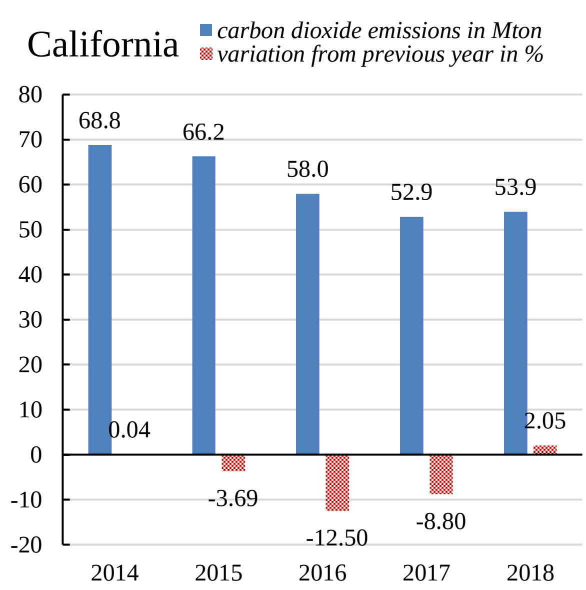


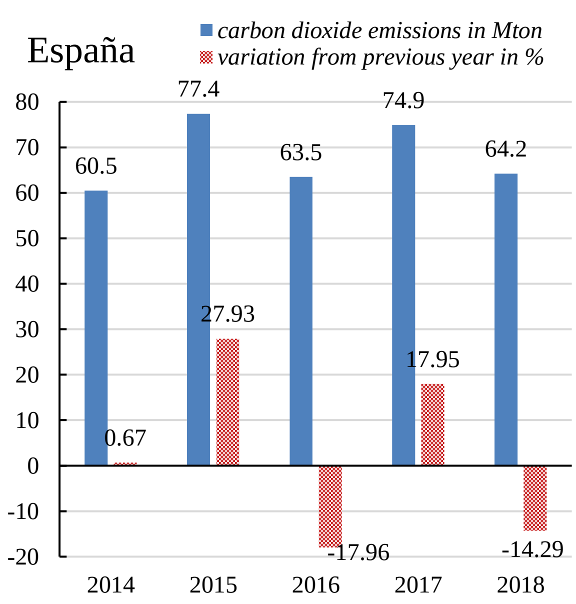
Para California se ha comparado el rendimiento de todas las plantas de energía solar térmica de concentración, independientemente de la tecnología empleada, llegando a los resultados proporcionados en la siguiente gráfica, que muestran los factores de capacitancia. Comparando los años mostrados, se puede observar cómo desde 2016 el factor de capacitancia medio ha ido decreciendo, al igual que el máximo y el mínimo.



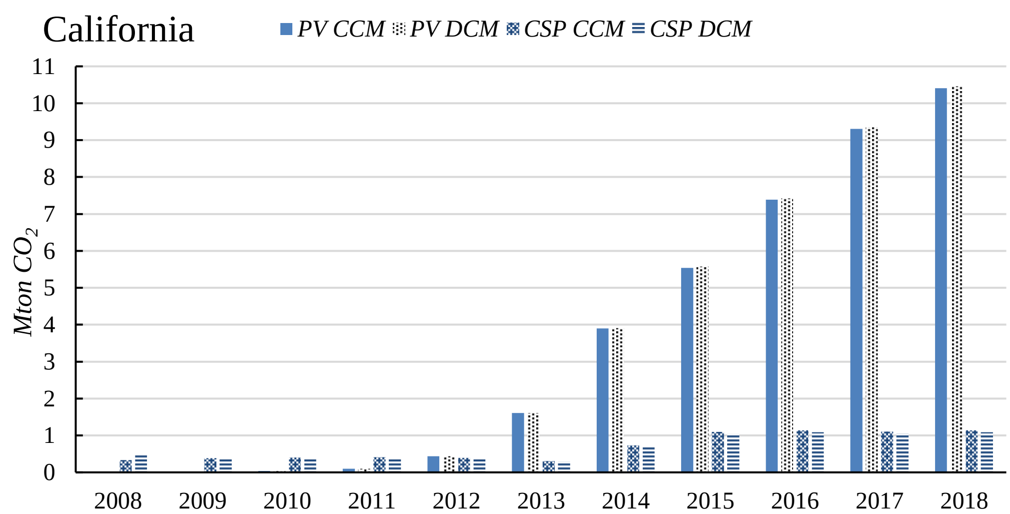
4. CARACTERISTICAS MEDIOAMBIENTALES DE LOS SECTORES ELÉCTRICOS

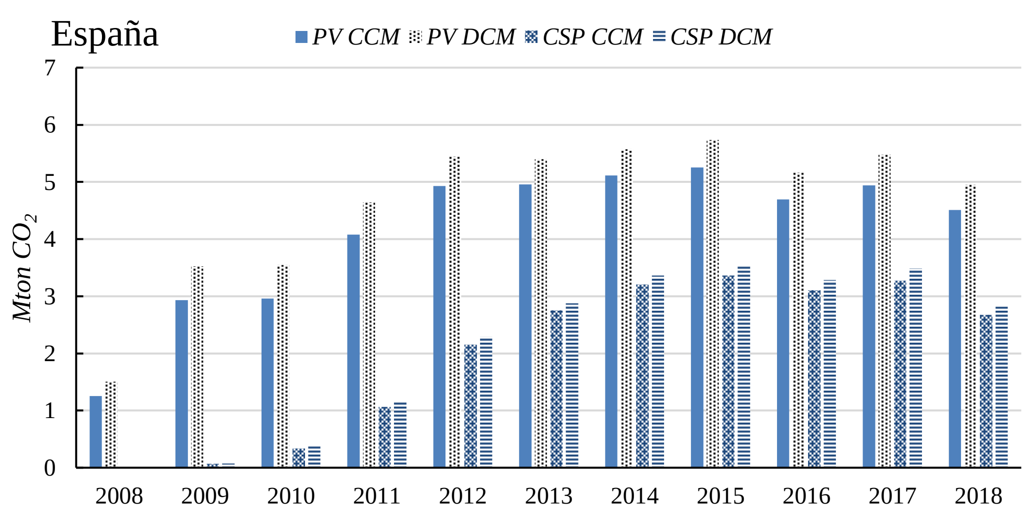
Los sectores eléctricos tienen asociada a la generación eléctrica unas emisiones de CO_2, que varían de año en año dependiendo de que fuente proviene dicha generación eléctrica. Cuanto más alta es la penetración de energía renovable en un año, menor son las toneladas de CO_2 asociadas a la producción energética, aunque este factor varía también dependiendo del tipo de combustible fósil que se ha utilizado. De este modo, un *GWh* generado en una planta de carbón emite más CO_2 que un *GWh* generado en una planta que utiliza gas natural como combustible para la generación de electricidad. A continuación, se observan las emisiones de CO_2 asociadas a la generación eléctrica en California y en España.





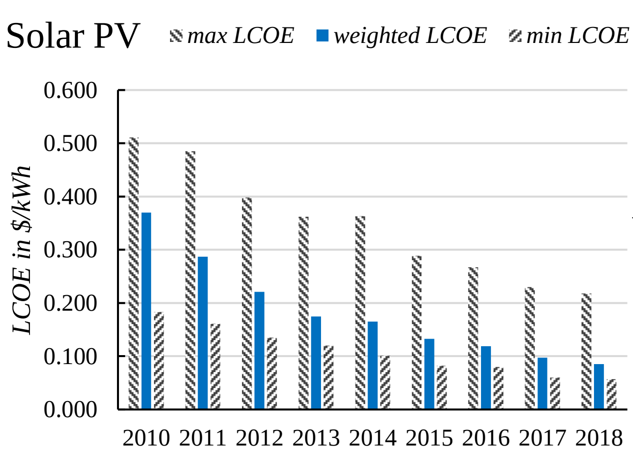
Para este proyecto, se ha querido calcular la cantidad de emisiones de CO_2 evitadas gracias a la producción de electricidad mediante energía solar. Para ello se han utilizado 2 métodos distintos. El primero de ellos, al que hemos llamado *CCM* ("Complex Computation Method"), es más complejo que el segundo, llamado *DCM* ("Direct Computation Method"). Las diferencias entre ambos métodos se encuentran en que *CCM* utiliza los coeficientes de emisión de CO_2 asociados a las diferentes tecnologías no renovables que emiten partículas de CO_2 a la atmósfera, así como coeficientes proporcionados por *IRENA* asociados a la energía solar fotovoltaica y térmica de concentración. Estos coeficientes son pequeños, pero tienen en cuenta las emisiones asociadas a la producción y distribución necesaria para la construcción de plantas de energía solar. *CCM* tiene en cuenta una hipotética distribución de como la energía anual generada por energía solar se hubiera distribuido en otras fuentes de energía no renovable, para un cálculo más exacto de las emisiones de CO_2 evitadas por la producción de electricidad mediante energía solar. El otro método, *DCM* utiliza directamente los coeficientes asociados a la generación de electricidad proporcionados por la "California Energy Comission" y "Red Eléctrica de España". A continuación, se muestran esos resultados en *Mton* de CO_2 asociadas a las tecnologías solar fotovoltaica y solar térmica de concentración mediante los dos métodos utilizados y en los dos territorios.

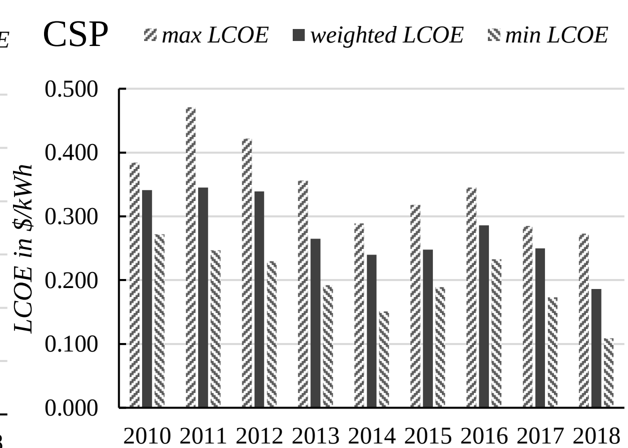




5. ANÁLISIS ECONÓMICO

En las dos gráficas siguientes, se visualiza la evolución del coste normalizado de la energía de la energía solar fotovoltaica y la energía solar térmica de concentración desde 2010 hasta 2018. Como se puede observar, el coste normalizado de la energía de la solar fotovoltaica ha disminuido considerablemente, mientras que el de la solar térmica de concentración ha experimentado oscilaciones, aunque resultando también en un descenso, aunque no tan pronunciado.





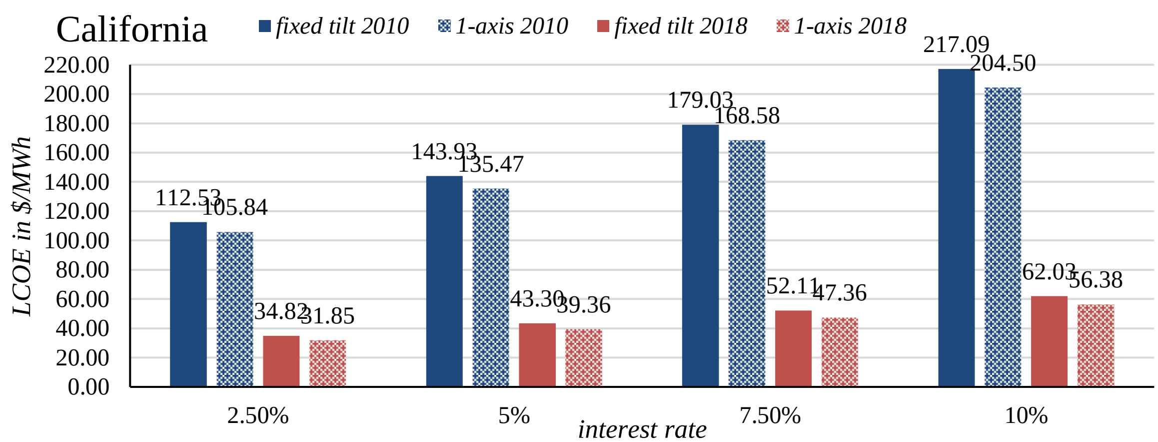
En este capítulo se ha querido comparar la evolución del coste normalizado de la energía de una hipotética planta fotovoltaica de 50 *MW* de inclinación fija o de seguidor a un eje, construida en 2010 o 2018, y en California o en España. Para ello, nos hemos basado en los datos proporcionados por el *NREL* sobre los costes de una planta fotovoltaica en 2010 y en 2018. Además, se ha buscado el precio del terreno tanto en California como en España de manera independiente. Para el cálculo del coste normalizado de la energía de esta hipotética planta se han realizado las siguientes supuestos:

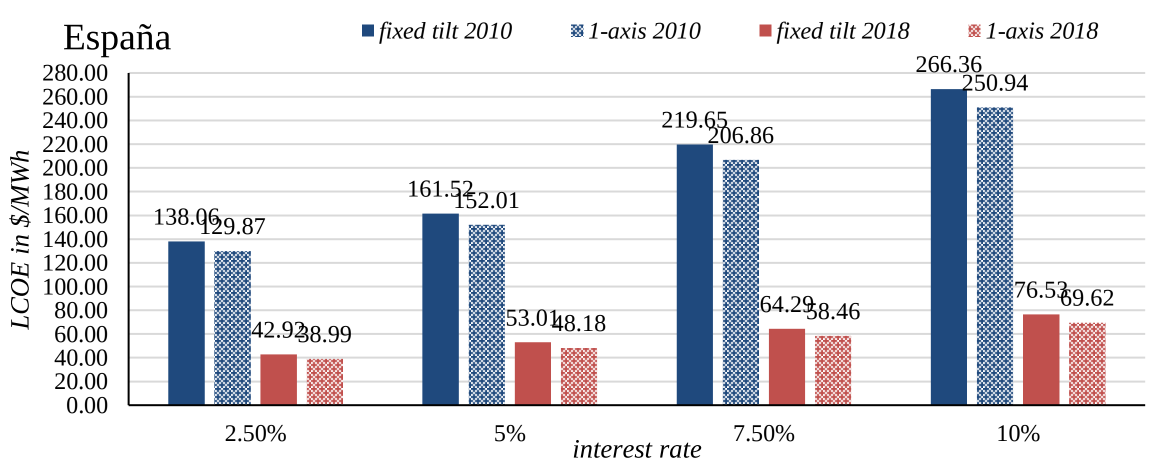
❖ Una radiación solar de 4.916 kWh/m^2-*dia* en España y de 6.018 kWh/m^2-*dia* en California.
❖ Un terreno de 1,000,000 m^2 si la planta fotovoltaica es de inclinación fija, con un incremento de un 20 % si utiliza seguidores a un eje.

- Un incremento de un 20 % en la producción de electricidad cuando la planta utiliza seguidores a un eje.
- Un factor de reducción combinado de 0.85. Este factor mide la eficiencia en la conversión de potencia en corriente continua a corriente alterna, teniendo en cuenta diferentes factores.
- Una disminución del 0.5 % anual en la generación de electricidad de la planta.
- 4 diferentes tasas de interés: 2.5 %, 5 %, 7.5 %, 10 %.

Utilizando la siguiente fórmula del coste normalizado de la energía, se llegan a los resultados de las siguientes gráficas para ambos territorios con diferentes tasas de interés.

$$LCOE = \frac{II + \Sigma_{t=1}^{n} \frac{O\&M_t}{(1+i)^t}}{\Sigma_{t=1}^{n} \frac{G_t}{(1+i)^t}} \left(\frac{\$}{MWh}\right)$$





6. CONCLUSIONES

En este proyecto se ha realizado una comparación a distintos niveles del rol de la energía solar dentro de la red eléctrica de 2 regiones protagonistas en el uso de energías renovables para generar electricidad. Del trabajo realizado podemos concluir que la energía solar fotovoltaica se está desarrollando de manera muy veloz y que, de forma clara, es la opción preferida comparada con la energía solar térmica de concentración. Aunque en un principio sobre el papel la energía solar térmica de concentración presenta ventajas como la posibilidad de almacenamiento, la realidad es que debido a los altos costes y al menor desarrollo que ha sufrido, ha pasado a un papel secundario. Se han calculado a su vez la cantidad de toneladas de CO_2 evitadas gracias a la producción de energía mediante fuentes solares, así como una comparación del coste nivelado de la energía entre ambos territorios, que pretende ilustrar el desarrollo que ha sufrido la energía solar fotovoltaica en un periodo de tan solo 8 años.

COMPARATIVE ANALYSIS OF THE SOLAR ENERGY ROLE IN THE SUPPLY OF ELECTRICITY IN SPAIN AND CALIFORNIA

Author: Maria Garcia, Michel.
Supervisor: Gross, George.
Collaborating Entity: University of Illinois at Urbana-Champaign.

EXECUTIVE SUMMARY OF THE PROJECT

1. INTRODUCTION

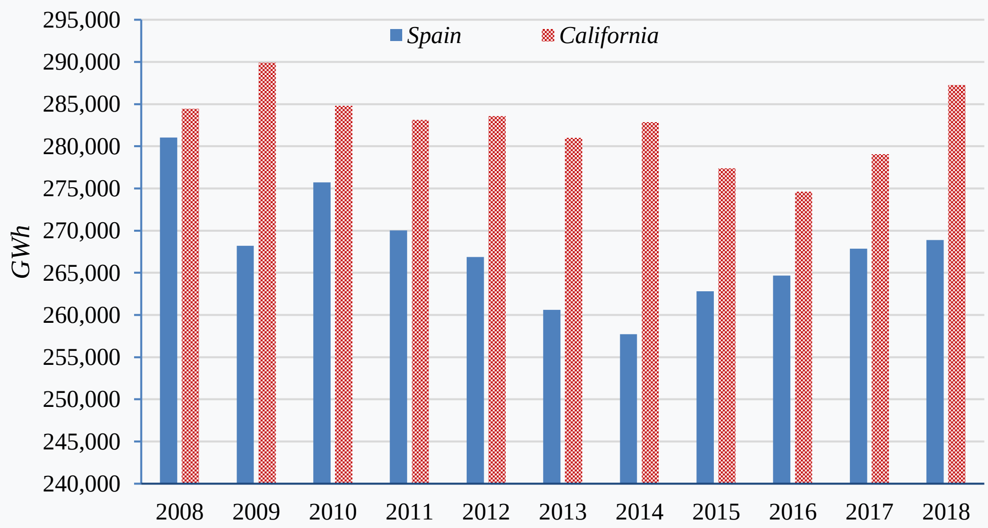
There is widespread concern about the need to reduce the amounts of CO_2 emissions that are emitted each year to effectively combat the impacts of climate change. The electrical power industry plays a key role worldwide, as it must be reliable and efficient to meet the energy needs of everyone connected to the grid, but at the same time, the electric power industry must contribute to the reduction of greenhouse gas emissions. To achieve this goal, the progressive introduction of renewable energy sources to replace fossil fuel-based energy sources plays a key role. Within the wide spectrum of options in terms of renewable energy sources, solar energy is a leading option, due to the great development in terms of efficiency combined with a large reduction in production costs in recent years. This project aims to carry out an analysis of how solar energy, photovoltaic solar (*PV*) and concentrated solar power (*CSP*), has evolved in two key territories within its geographical context, such as California within the United States of America and Spain within of Europe. These two territories are among the first to adopt solar technologies and have been at the forefront of their development. Throughout the execution of this project, the differences in the introduction of this type of technology in the network will be determined in the period studied between 2008 and 2018 and how the level of efficiency in terms of the capacitance factor is has developed over those years. For this, the main characteristics of the electrical systems of both regions will be studied: demand, electricity generation, the role of renewable energy, among other variables. In addition, a study of the CO_2 emissions avoided due to the generation of electricity using solar energy and a study of the differences in the *LCOE* of a photovoltaic plant between one region and another will be carried out.

2. OVERVIEW OF THE CALIFORNIA AND SPAIN REGIONS

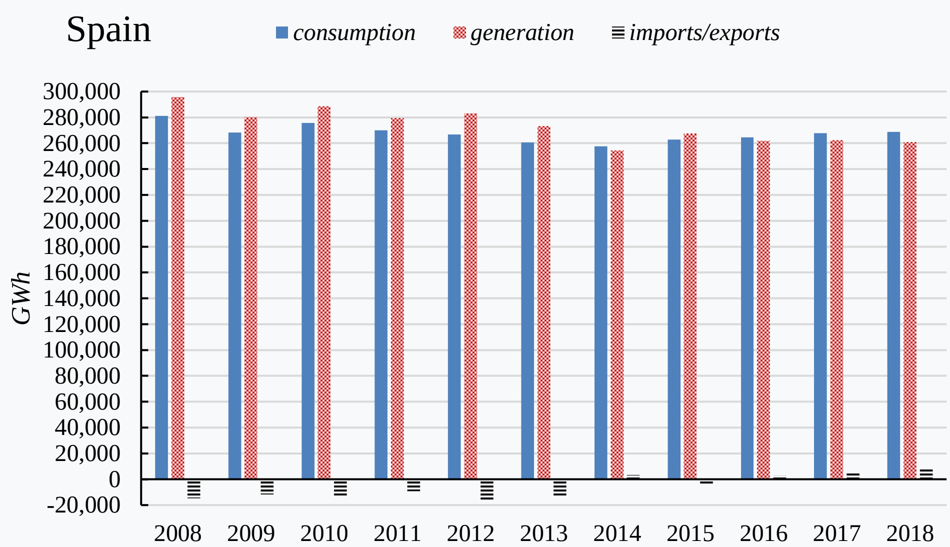
The comparison between these two territories is interesting because they present many similarities at a geographic and demographic level, the most notable difference being the gross domestic product, which is higher in California.

As for the electricity system, both territories have very similar annual peak loads, being in 2018 of 40,947 *MW* in Spain and 46,427 *MW* in California. These values are far from the record of peak load in both regions, which was reached in 2007 in Spain and in 2006 in California, having a similar variation of -11% with respect to that record of peak loadin the year 2018.

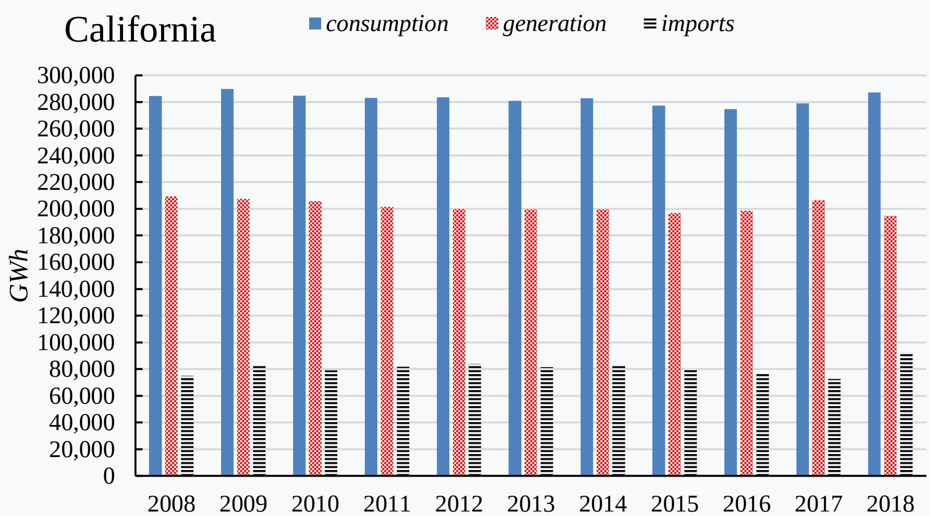
Annual electricity consumption is very similar during the period studied, as it can be seen in the following figure.



On the other hand, when we compare the in-region generation against the electricity consumption of both territories, the differences are clear. Spain has a generation which is very similar to the annual electricity consumption, which originates electricity imports / exports of very small values.

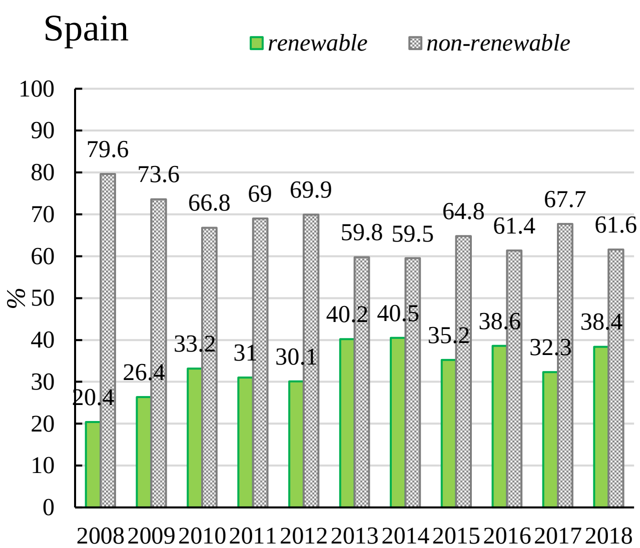


Instead, as can be seen in the following figure, California relies heavily on imports from neighboring states such as Oregon, Nevada or Arizona to satisfy its annual electricity consumption, covering electricity generation within the state approximately two thirds of the annual electricity consumption.

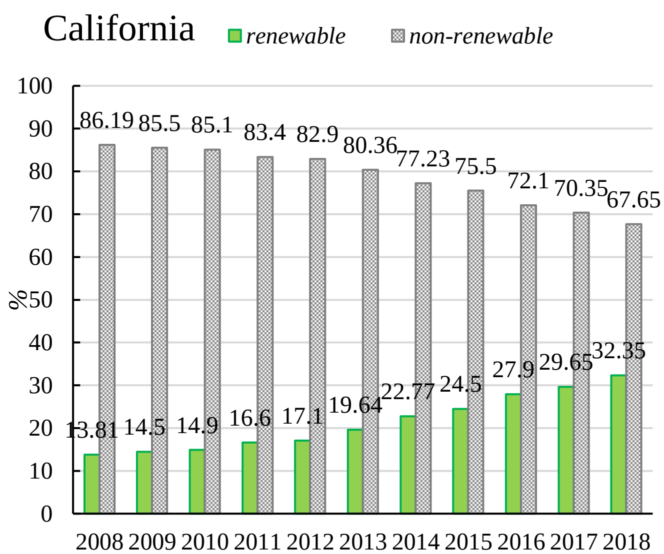


Comparing the electrical networks of both territories, large differences can be appreciated. Spain's electricity grid presents a greater variety of technologies that contribute to electricity generation, with a large presence of renewables. Instead, California's electricity grid relies heavily on 2 technologies: natural gas and hydroelectric plants, with a strong presence since 2015 from *PV* solar. When we compare the graphs of generation and installed capacity of both countries, there is a clear tendency to a decrease in the electricity generation year after year, when the installed capacity of the electricity grid is increasing. This is due to the progressive introduction of renewable energy into the grid.

Finally, the evolution of the renewable presence within electricity generation can be observed in the following two graphs, with Spain remaining above 30% of renewable generation since 2010, reaching a peak of 40.5 *%* in 2014, and with California in clear ascension due to the large investment in photovoltaic solar mainly, exceeding for the first time the threshold of 30 *%* in 2018.



(Renewable include hydro, hydropower, wind, solar PV and CSP, other renewables and renewable waste)

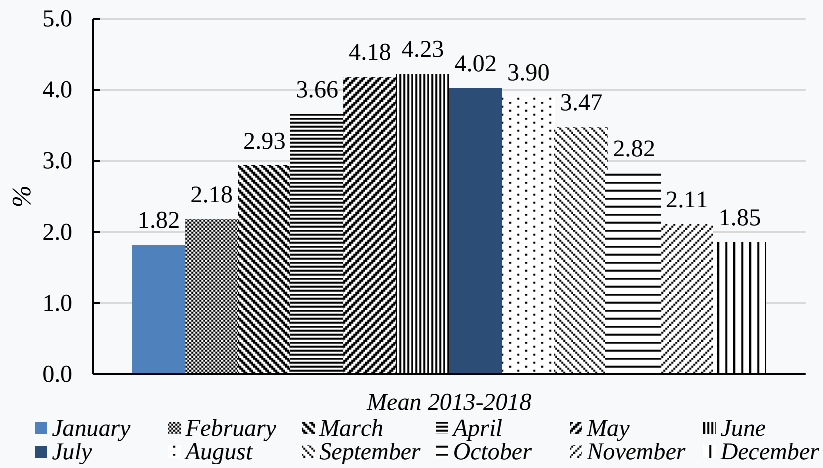


(Renewable include hydro, solar PV and CSP, wind, biomass and geothermal)

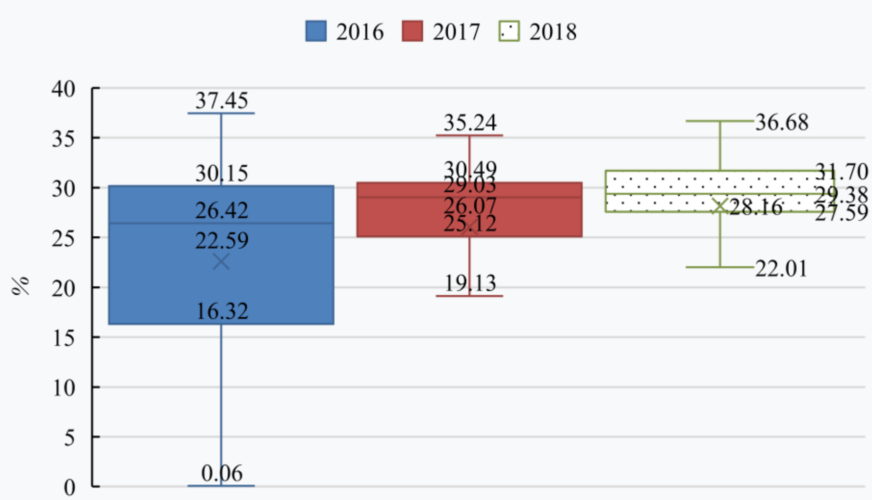
3. COMPARATIVE ASSESSMENT OF SOLAR RESOURCES IN CALIFORNIA AND SPAIN

Solar irradiation is a key aspect for the functioning and performance of *PV* solar and *CSP*. Comparing the main areas where concentration photovoltaic and thermal plants are built in Spain and California, a higher average irradiance is seen in California, so the expected performance there will be higher compared to Spain, as it will be seen in the project. *PV* solar energy has followed different paths in both territories. In Spain, the installed capacity has stayed constant around 4,600-4,700 *MW* since 2013, while in California, the installed capacity has been increasing since 2008, reaching over 10,000 *MW* of installed power in 2018. As for the capacity factor of photovoltaic solar energy, there are also differences, with the capacity factor barely reaching 20 % in Spain, while in California this value rises to 26 %.

Different analysis, such as those shown below have been developed in this project. The following graph shows the monthly percentage with respect to the total generation of electricity from photovoltaic solar energy in Spain. We can see how from 2013 to 2018, in the summer months, more than 4 % of the generation is from *PV* solar, a value that drops to less than 2 % in winter months.

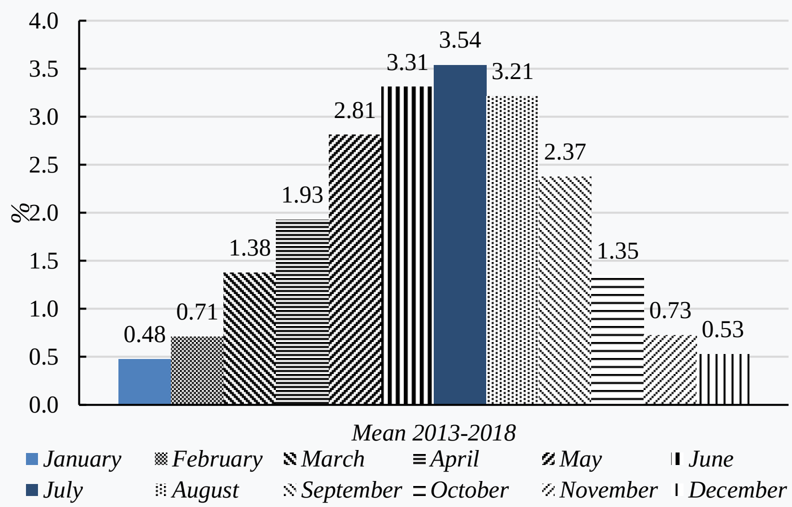


In the case of California, we have analyzed the performance of all photovoltaic plants with an installed capacity greater than 20 *MW*, due to the large number of these plant type compared to Spain. We can see how, in the box diagram, performance improves year by year as *PV* solar energy strengthens and matures as a technology.

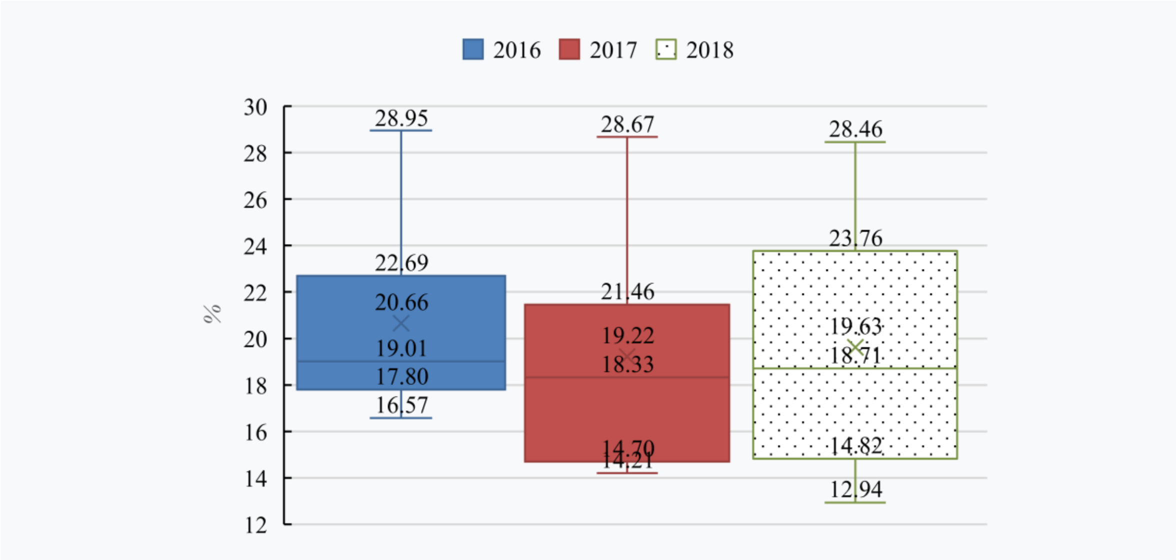


In the case of *CSP*, there is a certain similarity with respect to development in both regions. The first parabolic trough plants (Solar Electric Generating Stations) were built in the mid-1980s in California, while Spain was the first country in Europe to adopt this type of technology back in 2008. Both regions are pioneers in the development of this technology worldwide. Even the investment in this technology "stopped" practically at the same time, since in Spain there has been no new plant additions to the grid since 2013, while in California it is since 2014, when 3 large projects were connected to the grid.

The following graph shows the monthly percentage with respect to the total generation that *CSP* provides in Spain. We can see how from 2013 to 2018, in summer months, the percentage of production even exceeds 3.5 % of the total generation, a value that drops dramatically to less than 0.5 % in the month of January.

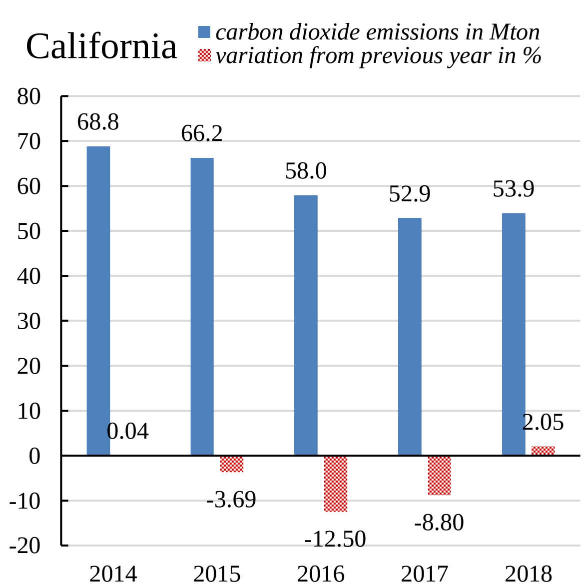


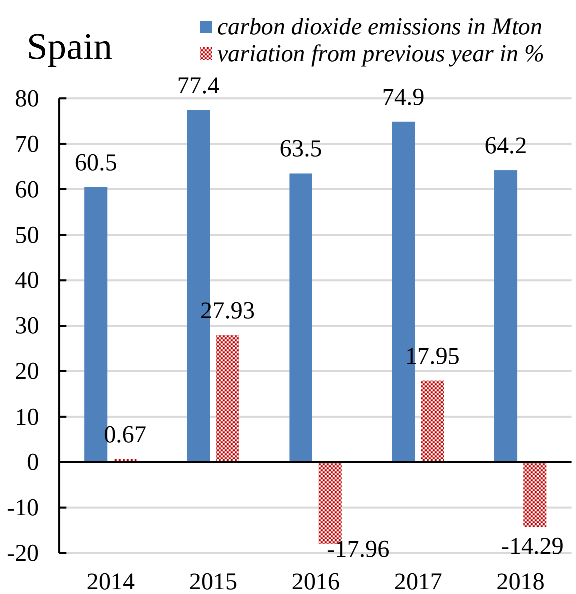
For California, the performance of all concentrated solar thermal power plants has been compared, regardless of the technology used, reaching the results provided in the following graph, which show the capacity factors. Comparing the years shown, it can be seen how since 2016 the average capacity factor has been decreasing, as well as the maximum and minimum.



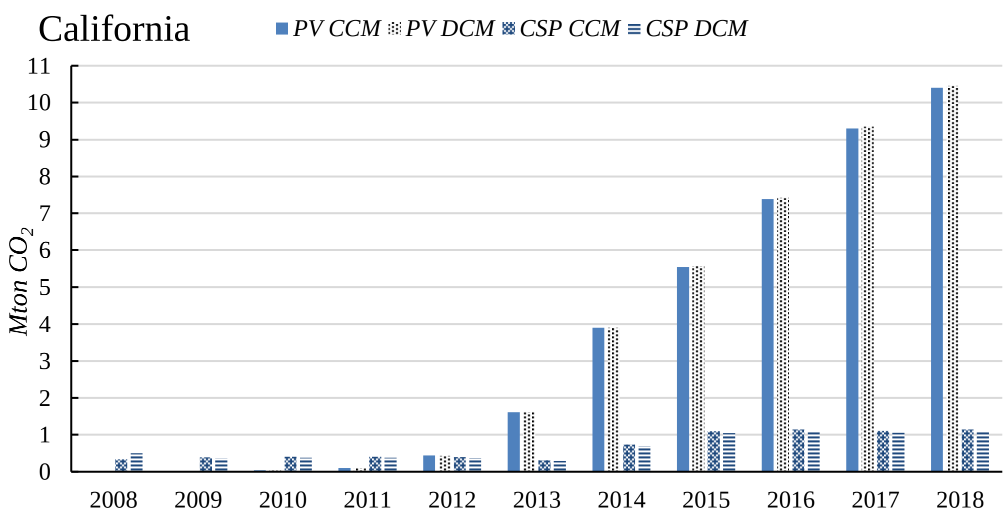
4. ENVIRONMENTAL CHARACTERISTICS OF THE ELECTRICITY SECTORS IN CALIFORNIA AND SPAIN

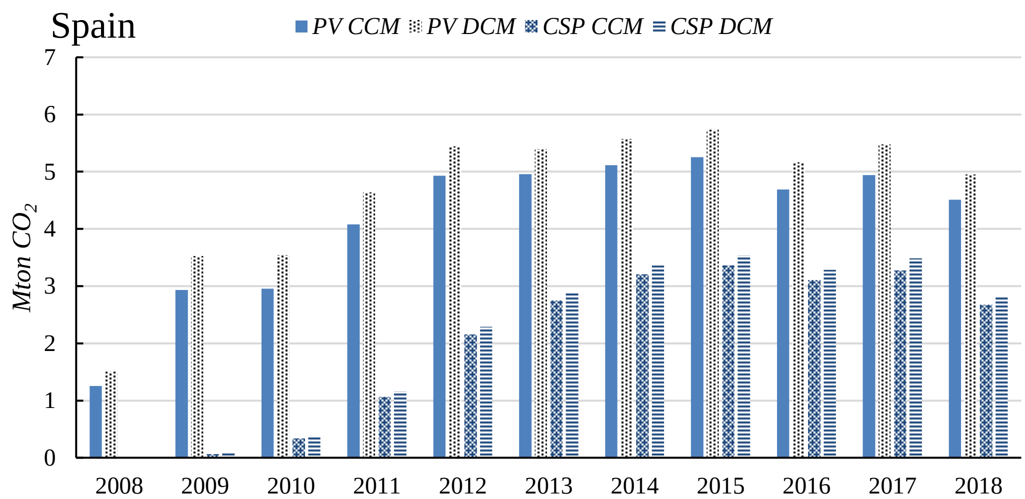
The electricity sectors have CO_2 emissions associated with electricity generation, which vary from year to year depending on the source of said electricity generation. The higher the penetration of renewable energy in a year, the lower the tons of CO_2 associated with energy production, although this factor also varies depending on the type of fossil fuel that has been used. In this way, a *GWh* generated in a coal plant emits more CO_2 than a *GWh* generated in a plant that uses natural gas as fuel for electricity generation. Below are the CO_2 emissions associated to electricity generation in California and Spain.





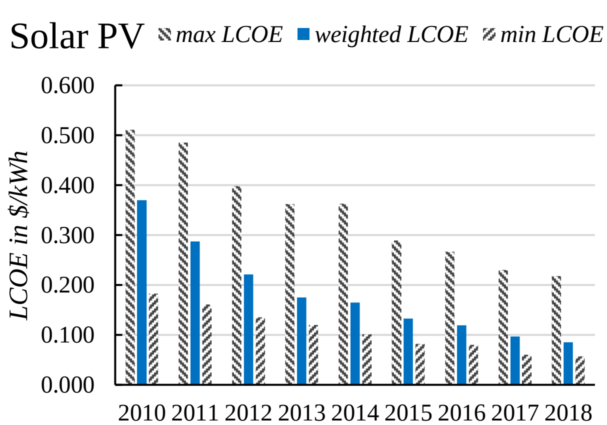
For this project, we wanted to calculate the amount of CO_2 emissions avoided thanks to the production of electricity using solar energy. For this, 2 different methods have been used. The first of these, which we have called *CCM* ("Complex Computation Method"), is more complex than the second, called *DCM* ("Direct Computation Method"). The differences between the two methods are that *CCM* uses the CO_2 emission coefficients associated with the different non-renewable technologies that emit CO_2 particles into the atmosphere, as well as the coefficients provided by *IRENA* associated with concentrated photovoltaic and thermal solar energy. These coefficients are small but take into account the emissions associated with the production and distribution necessary for the construction of solar power plants. *CCM* considers a hypothetical distribution of how the annual energy generated by solar energy would have been distributed in other non-renewable energy sources, for a more accurate calculation of the CO_2 emissions avoided by the production of electricity by solar energy. The other method, *DCM* directly uses the coefficients associated with electricity generation provided by the "California Energy Commission" and "Red Eléctrica de España". These results are shown below in *Mton* of CO_2 associated with solar photovoltaic and concentrating solar technologies using the two methods used and in the two territories.

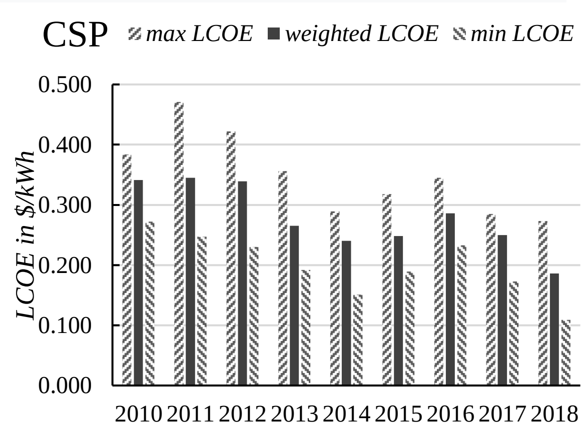




5. ECONOMIC ANALYSIS

In the following two graphs, the evolution of the normalized cost of photovoltaic solar energy and concentrated solar energy from 2010 to 2018 is displayed. As can be seen, the normalized cost of solar photovoltaic energy has decreased considerably, while that of the concentration solar thermal has experienced oscillations, although also resulting in a decrease, although not as pronounced.



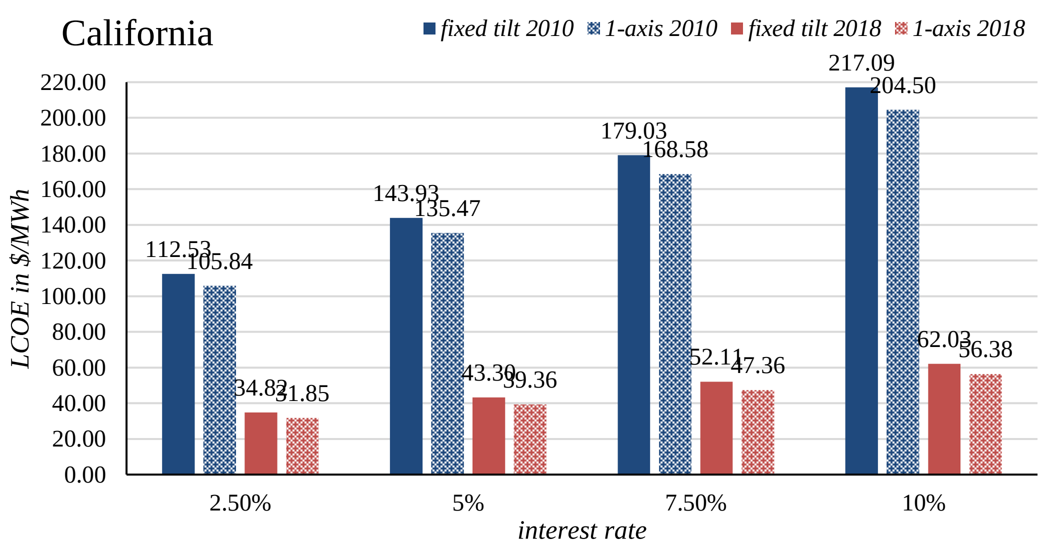


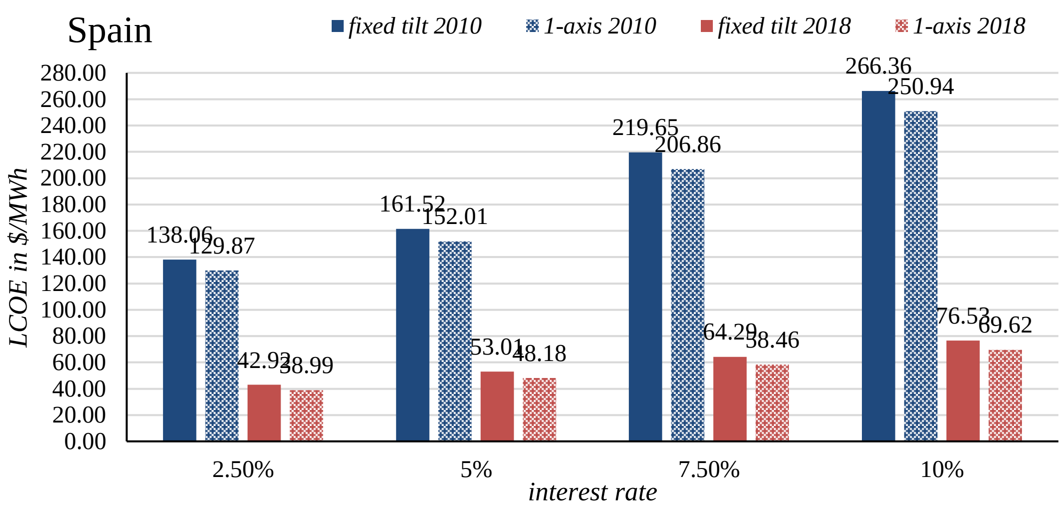
In this chapter we wanted to compare the evolution of the normalized cost of energy of a hypothetical 50 MW photovoltaic plant with fixed inclination or follower to an axis, built in 2010 or 2018, and in California or Spain. For this, we have relied on the data provided by the NREL on the costs of a photovoltaic plant in 2010 and in 2018. In addition, the price of the land has been sought both in California and in Spain independently. The following assumptions have been made to calculate the normalized cost of energy for this hypothetical plant:

- Solar radiation of 4,916 *kWh/m²-day* in Spain and 6,018 *kWh/m²-day* in California.
- A land of 1,000,000 m^2 if the photovoltaic plant is of fixed inclination, with an increase of 20 % if it uses trackers to one axis.
- A 20 % increase in electricity production when the plant uses one-axis trackers.
- A combined derate factor of 0.85. This factor measures the efficiency in converting power from direct current to alternating current, taking into account different factors.
- A 0.5 % annual decrease in the electricity generation of the plant.
- 4 different interest rates: 2.5 %, 5 %, 7.5 %, 10 %.

Using the following formula for the normalized cost of energy, the results of the following graphs are obtained for both territories with different interest rates.

$$LCOE = \frac{II + \Sigma_{t=1}^{n} \frac{O\&M_t}{(1+i)^t}}{\Sigma_{t=1}^{n} \frac{G_t}{(1+i)^t}} \left(\frac{\$}{MWh}\right)$$





6. CONCLUDING REMARKS

In this project, a comparison has been made at different levels of the role of solar energy within the electricity grid of 2 leading regions in the use of renewable energy to generate electricity. From the work carried out, we can conclude that photovoltaic solar energy is developing very quickly and that it is clearly the preferred option compared to concentrated thermal solar energy. Although concentrating solar energy initially has advantages such as storage on paper, the reality is that due to the high costs and less development it has undergone, it has moved to a secondary role. In turn, the amount of tons of CO_2 avoided thanks to the production of energy by solar sources has been calculated, as well as a comparison of the leveled cost of energy between both territories, which aims to illustrate the development that photovoltaic solar energy has undergone in a period of only 8 years.

ABSTRACT

Solar energy resources have become one of the greatest options among renewable energy sources around the world, as they have had a huge development in terms of technical efficiency, that have come alongside with a great reduction of the manufacturing cost during recent times. These two factors combined, made solar energy very attractive as an energy source, especially in a world with increasing need in terms of energy consumption, and with the urgency of reducing CO_2 emissions that pollute the atmosphere. The main objective of this thesis is to provide a better understanding of the two solar energy technologies, solar photovoltaic (*PV*) and concentrated solar power (*CSP*) have evolved over the last decade in two key regions in the world – California in the *US* and *Spain* in *Europe*. These two regions are among the early adopters of solar of technologies and have been at the forefront of its rapid development. We shall determine what have been the differences in the introduction of these technologies into the grid during the period studied, from 2008 to 2018 and how the level of performance in terms of the capacity factor (*c.f.*) has developed during those years. For doing so, we will determine the main characteristics of the electricity power systems of both regions, the consumption, in-region generation, peak load, role of renewables in the grid among others, to then focus on solar *PV* and *CSP*. We will look at the evolution of the capacity installed and generation of both technologies in both regions, how the level of performance has been year to year, to then make an analysis on the amount of CO_2 emissions avoided by the electricity generation of solar resources using two different methods. Also, a brief analysis on the difference in cost and the levelized cost of energy of solar *PV* and *CSP* is made.

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1. INTRODUCTION

In this chapter we set the stage for the work presented in this thesis. The main interest lies on the contribution of solar resources during the period between the years 2008 and 2018 in the regions of California and Spain, how the implementation in the grid of solar photovoltaic (*PV*) and concentrated solar power (*CSP*) technology for electricity generation has evolved over that decade.

1.1 Overview of the scope and nature of the issues discussed in the report

There is a general concern about the need to reduce the amounts of CO_2 emissions that are emitted every year to effectively combat climate change impacts. The electric power industry plays a major role worldwide, as it needs to be reliable and efficient to satisfy all the energy needs of everyone connected to the grid, but at the same time, the electric power industry needs to help in the reduction of greenhouse gas (*GHG*) emissions. With the continuous introduction of renewable energy sources into the grid, the electric power industry deals with the reduction of *GHG* emissions, with the aim at the same time to progressively displace costly and polluting fossil-fuel-fired conventional technologies, Also, the introduction of renewable energy sources in any region decreases the dependence on the import of the fossil-fuels for the conventional power plants to generate electricity. Among all these different types of renewable energy sources, we find the two that extract energy from the sun, solar *PV* and *CSP*. These are technologies whose evolution and development has been different, even if both technologies extract the energy from the sun, as the process to be able to extract that energy from the sun to produce electricity is very different in both technologies. The basic procedure on how electricity is made for both technologies will be explained in chapter 3. The penetrations of both solar technologies in the grid are very different in different parts of the world, so it is of considerable interest to compare two regions, both with good solar irradiation. The way solar *PV* and *CSP* have developed in two of the main international standard bearers of these technologies would bring insights of how these technologies have evolved over the period that covers the years 2008 to 2018.

1.2 Contribution

For this report, as a comparative analysis, based on the solar energy role in the supply of electricity, lots of data from the electricity sector from each region were needed. This data includes the characteristics of the electricity generation, the demand, and the role renewable energy sources play in the grid compared to non-renewable energy sources. The principal organizations from which we have extracted the data to carry out the project have been the California Independent System Operator (*CAISO*) and the California Energy Commission in the case of California and Red Eléctrica de España (*REE*) in the case of Spain. In addition, data from big international agencies like the International Renewable Energy Agency (*IRENA*) and the International Energy Agency (*IEA*) was also used throughout the realization of the project. The main contribution of this work is to provide an analysis on how both technologies have evolved and developed in two key regions for solar energy resources. This work also intends to provide a better understanding on how the same technologies have followed very different paths in regions that are very similar in solar power energy potential. From a personal point of view, the realization of this work, has helped myself further my knowledge on renewables, especially in solar resources.

1.3 Outline of the report

This thesis contains 5 additional chapters and 3 appendixes:

In chapter 2, we provide an overview of the regions of California and Spain, taking a close look and how the grid and the generation resource characteristics have evolved in the period 2008 – 2018, with a focus on how the role of renewable energy sources has developed over the years.

In chapter 3, we study the situation of solar *PV* and *CSP* in the two regions. Specifically, we analyze the characteristics that are common to both regions in solar *PV* and *CSP* in the grids of the two regions and also at their distinctly different characteristics. We also investigate the respective efficiency achieved by the two solar technologies in California and Spain.

In chapter 4, we investigate the role solar energy resources play in the reduction of CO_2 emissions via the deployment of two different methods to calculate the amount of emissions avoided to go into the atmosphere. Also, we provide some insights into the role of both the Paris Agreement and the Kyoto Protocol in the formulation of the objectives in the reduction of CO_2 emissions and the responses by the California and Spain electric power sector to meet the specified goals for their respective region.

In chapter 5, we briefly examine the evolution of investment costs of the two solar technologies – *PV* and *CSP* – as well as, the corresponding levelized costs of energy (*LCOE*) of both technologies. In addition, we provide an economic analysis of a hypothetical 50 *MW PV* plant, calculating its *LCOE* for several scenarios.

In chapter 6, we summarize the conclusions and results that will be extracted from chapters 2 to 5.

In Appendix A, we provide a brief reflection on how this project is related to some of the Sustainable Development Goals (*SDG*s) created by the United Nations.

In Appendix B, we provide the data related to the annual generation and the capacity installed year by year in Spain and California, that was used to do the figures in chapter 2.

In Appendix C, we provide the list of all the *CSP* projects in California and Spain with their principal technical characteristics.

2. OVERVIEW OF THE CALIFORNIA AND SPAIN REGIONS

In order to assess how Solar *PV* and *CSP* have developed through 2008 to 2018 in both regions, California and Spain, it is necessary to have a general view on what are the general characteristics of those regions, as well as the specific characteristics related to the electricity power sector, as are the electricity demand, the electricity in-region generation or how what the technologies that conform both grids and how they have evolved during these last 12 years, when renewable energy sources have experimented a relative high growth and there is rising willing in these renewable technologies to get rid of fossil-fuel based technologies which pollute much more.

2.1. Comparative assessment of the regions' geographic, demographic, energy, environmental and economic characteristics

California and Spain are two territories that have many features in common and so a comparative analysis makes sense. In this chapter, we compare quantitatively some of these features.

Table 2.1: Spain and California geographic data

region	total area (km^2)	land area (km^2)	water area (km^2)
Spain	505,990	500,728	5,262
California	423,970	403,932	20,047

In table 2.1 we can see the geographic data from California and Spain, while in Table 2.2 we can see the demographic data. California is the largest in population of the 50 states that comprise the United States of America and the third largest in terms of area, just behind Alaska and Texas, with a total area of 423,970 km^2. Its territory covers latitudes from 32º – 42º N. Spain is Europe's fourth largest country and lies between latitudes 36º – 44º N and from 27º – 44º N if we also include the Canary Islands. Its total area covers 505,990 km^2.

Table 2.2: Spain and California demographic data

region	population in 2010	population in 2019	Increase from 2010 to 2019 in %
Spain	46,815,916	47,007,367	0.4
California	37,235,956	39,512,223	6.1

Combining the data from Table 2.2 and Table 2.3 we can compute the density of population, which turns out to be very similar between both territories, having California a slightly bigger density of population, with 97.9 inhabitants per km^2 compared to the 92 inhabitants per km^2 that Spain has.

As part of the comparison, we also need to consider the peak load of the two regions. We provide the respective values together with the historical peak load in Table 2.3.

Table 2.3: Spain and California annual electricity peak load values

region	2019	2018	variation from 2019 to 2018 in %	historical record peak	variation from to 2019 to historical record in %
Spain	40,455 *MW*	40,947 *MW*	- 1.2 *%*	45,450 *MW*	- 11.0 *%*
California	44,301 *MW*	46427 *MW*	- 4.57 *%*	50,270 *MW*	- 11.87 *%*

In Spain, the maximum peak load of the year 2019 [18] was 40,455 *MW* on January 22 at 20:08, a 1.2 *%* reduction from the peak load of the previous year, and 11 *%*, from the maximum peak load record from 2007. The California peak load [1] in 2019 was 44,301 *MW* on August at 15 17:50 – a significant reduction of 4.57 *%* below the 2018 value and and 11.87 *%* from the historical record peak of 2006.

Both regions have experienced a reduction in their annual peak loads and have approximately a similar percentage decrease from their record values. While one may interpret such a reduction in each region as due to the efficiency improvements, which have definitely been implemented in the two grids, an equally important reason is the amount of solar PV autonomous generation by the end-use customers, both residential and commercial/ industrial users. It is interesting that the annual peak load in each year in Spain is typically reached in the winter months of January and December in the evening. California, on the other hand, experiences the annual peak load in the summer months of July, August and September and at an earlier time of the day in the afternoon.

The biggest differentiating factor between the two regions arises from their economic outputs [2,3]. California, on its own, has the largest economy among the 50 *US* states. Indeed, if California were a sovereign nation on its own, it would rank as the sixth largest economy in the world, behind the *US, China, Japan, Germany* and *India*, and just above *UK* and *France*. Meanwhile, Spain ranks as the 13th world's economy, being the 5th largest economy of the eurozone, behind *Germany, UK, France* and *Italy*. As it is clearly noticeable, there is a big difference between the *GDP* per capita, either *PPP* or nominal, between both territories. The *GDP* is the Gross Domestic Product and is the monetary value of all final goods and services made within a country or region during a specific period, normally a year. It provides a good look and evaluates accurately a country or region economy. The *GDP* nominal is useful for large-scope *GDP* comparison, especially in an international scale, but it does not reflect the cost of living or the inflation rates. On the other hand, The *GDP PPP* (Purchasing Power Parity) does consider the cost of living. Both systems have its pros and cons and are useful depending on what situations.

Table 2.4: Spain and California *GDP*'s

region	***GDP* (*PPP*) total (trillion $)**	***GDP* (*PPP*) per capita ($)**	***GDP* (nominal) total (trillion $)**	***GDP* (nominal) per capita ($)**
Spain	2.016	43,007	1.44	30,734
California	3.0	75,966	2.314	58,619

2.2. Electricity consumption, supply and grid in California and Spain

The consumption of both regions is similar in terms of *GWh* consumed per year, as we can see in Figure 2.1 below, although California has a higher electricity consumption per year throughout the period studied.

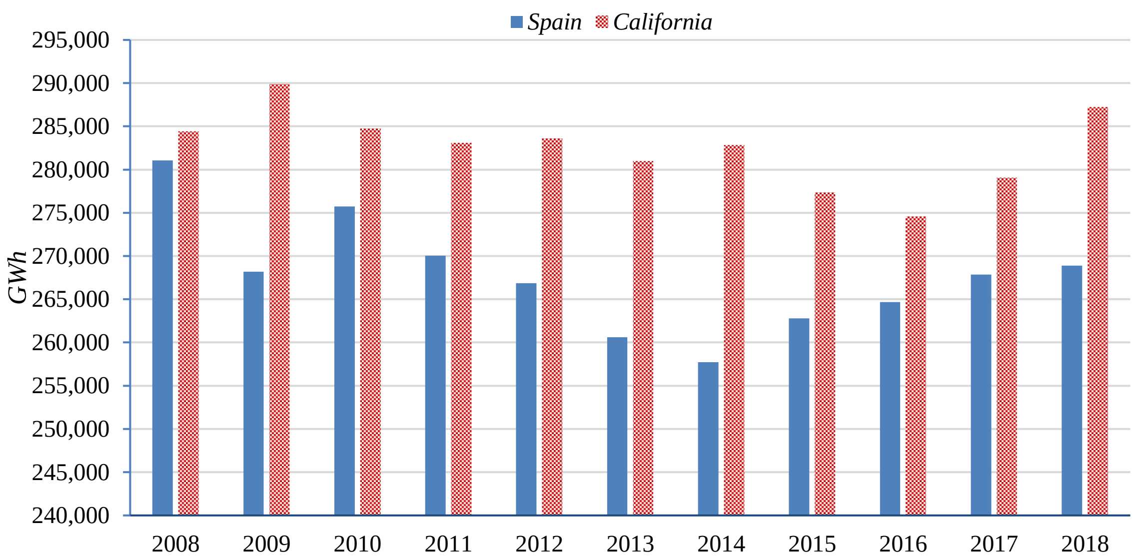


Figure 2.1: Electricity consumption in Spain and California [4,5]

California's biggest energy consumption was in 2009 with 289,912.51 *GWh* and has followed a decreasing tendency, being in 2016 when less energy was needed, with 274,600.9 *GWh*. Spain on the other hand had its biggest energy consumption back in 2008, with 281,051.4 *GWh*, which decreased heavily in 2009. It followed a decreasing tendency in terms of energy during the following years, coinciding with the years of the economic repression. It reached its lowest electricity demand in 2014, when 257,719.9 *GWh* were needed. The consumption has grown at a steady rate the following years.

Although, California's electricity consumption is higher than Spain's one, the way to satisfy the load its very different between both regions. Spain covers practically all its electricity consumption with its own in-region generation, and depending on the year, imports or exports little amount of energy from *Portugal* or *France*, the 2 countries to which the Spanish grid is connected to. In Figure 2.2 we can see the evolution of the electricity consumption, electricity generation and the imports/exports from 2008 to 2018. For example, in 2008, Spain exported 14,842.1 *GWh* of energy, while in 2018 it imported 7,903.8 *GWh*.

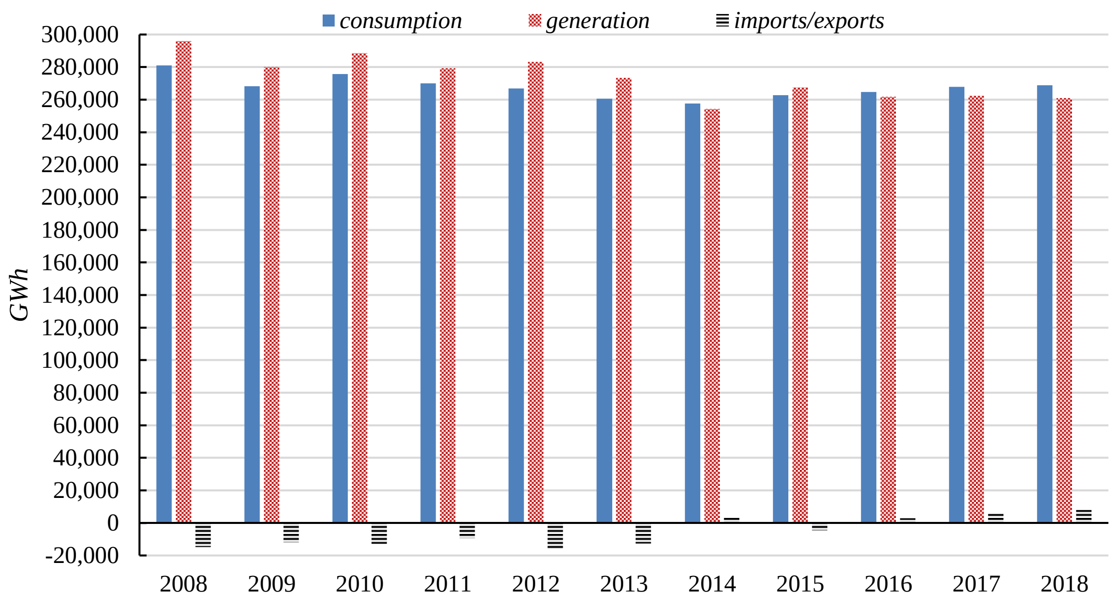


Figure 2.2: Electricity consumption compared to in-region electricity generation in Spain [4,6]

California instead is unable to meet its energy consumption just by the in-region generation, as we can see in Figure 2.3, despite having one of lowest energy consumption per capita rate in the United States. It relies in huge amount of imports from other states like Nevada or Oregon, being the state which imports more electricity among the 50 that conform the United States of America. Imports are around 80,000 *GWh* per year, from different sources, renewable and non-renewable, but in 2018, they grew up to 92,522.49 *GWh*.

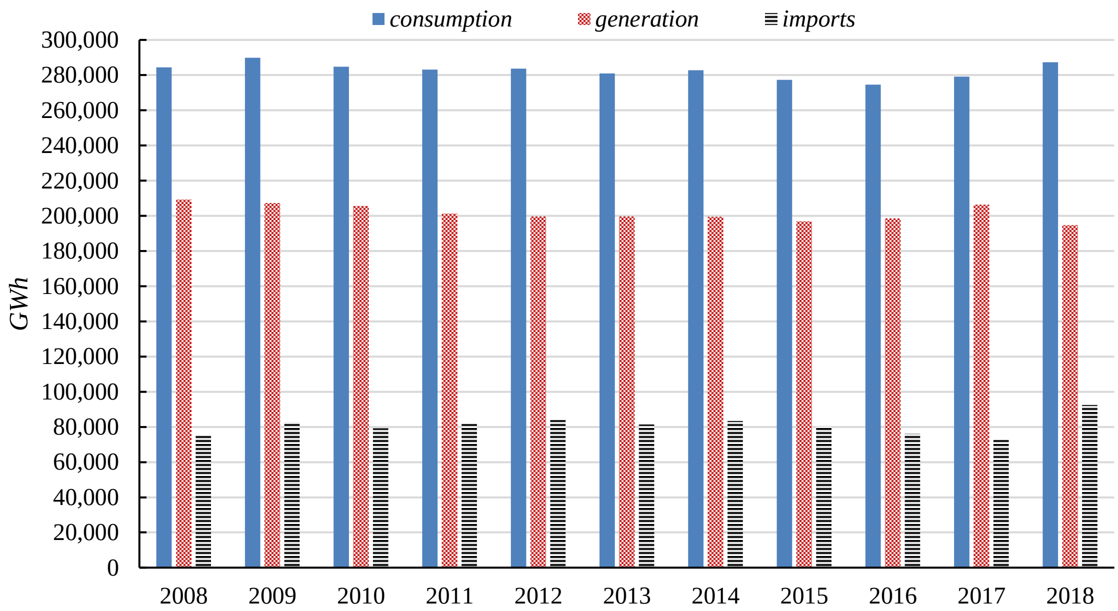


Figure 2.3: Electricity consumption compared to in-region electricity generation in California [5, 19-28]

In Spain the total net generation has followed a decreasing tendency over the last decade, as it can be seen in Figure 2.4. In 2008, the total generation was 295,893.5 *GWh*, amount that has decreased over the years, achieving its minimum in 2014 with 254,359.7 *GWh*, and remaining quite stable from 2016 to 2018 at approximately 260,000 *GWh*. This means, that now, Spain needs 35,000 *GWh* less than in 2008, a decrease of more than 11 *%*, which is a considerable difference. How this energy has been produced has changed over the years, due to the irruption of new technologies and the impulse of renewable energy.

Nuclear is the source of energy that has remained most stable from 2008 to 2018, providing more than 50,000 *GWh* each year, which translates to nearly 20 *%* of the totally energy produced each year. Combined cycle plants, on the other hand, have decreased from a 31,5 *%* of the total energy generated in 2008, to barely a 10 *%* since 2014. In 2008 it contributed with 93,197.5 *GWh* while in 2014 it only provided 24,828.8 *GWh* more than 3 times less energy. It is well-known that Spain is one of the countries that has one of the strongest wind energy production, thanks to a lot of investment in this type of technology and that a vast part of its territory its suitable to this type of technology. In 2008, it already produced more than 32,000 *GWh*, which meant a 10 *%* of the total energy produced in that year. In 2013, it reached its peak with 20 *%* of the energy produced (54,713.4 *GWh*), and over the last few years it has been producing just under 50,000 *GWh*, an approximately 18 *%* of all the energy produced. Solar energy instead has followed a different path. In 2008, *CSP* presence in the grid was marginal, with only 15.4 *GWh* produced. It is not until 2012, when the majority of projects have been finished and its contribution to the grid is 'noticeable', surpassing the 1 *%* of total energy produced with 3,447.5 *GWh*. Since then, a few more projects were connected to the grid, and know *CSP* produces about 2 *%* of the total energy, at around 5,000 *GWh*. Solar *PV* presence in the grid has been bigger. In 2008 it produced almost 2,500 *GWh*, jumping to more than 6,000 *GWh* in 2009. Since 2012, with only few and small projects created, its contribution has remained stable at around 8,200 *GWh*, which means around a 3 *%* of all the energy produced in a year in Spain. Generation from hydro sources vary a lot from year to year, between 7 *%* and 14 *%* of the total energy produced.

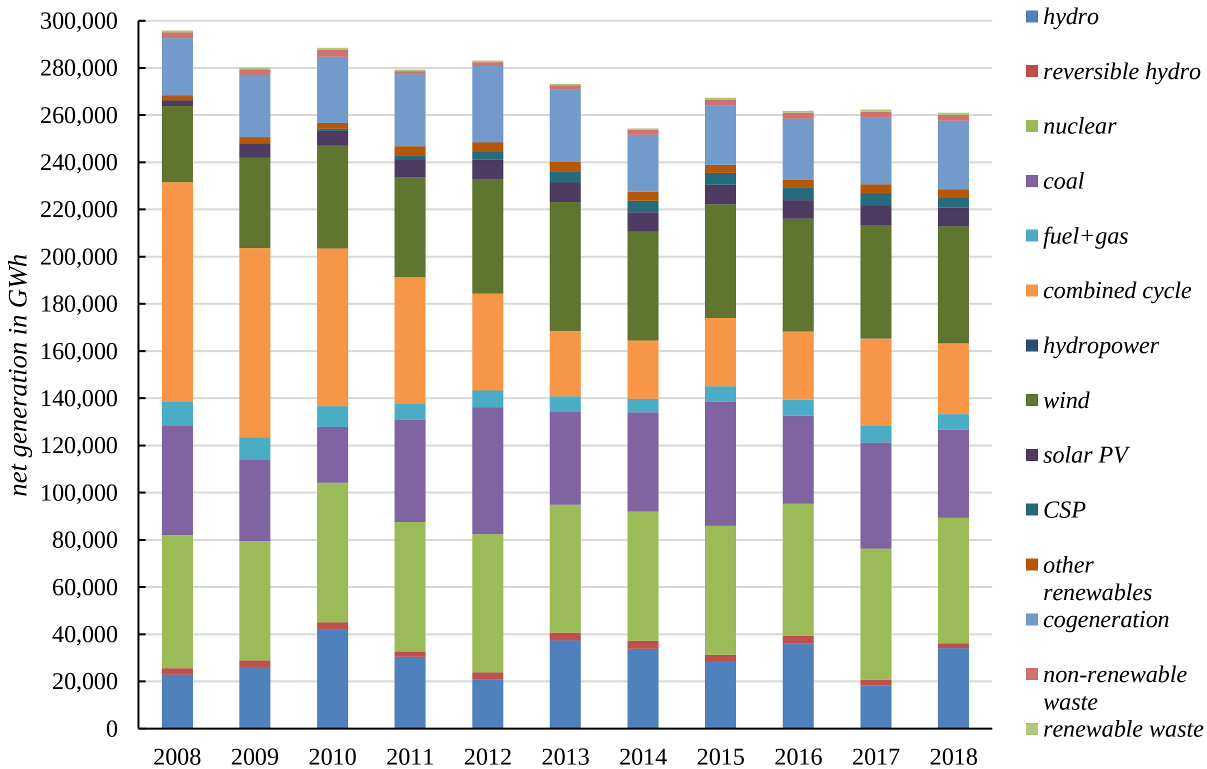


Figure 2.4: Share of the net electricity generation in Spain by technologies in *GWh* [6]

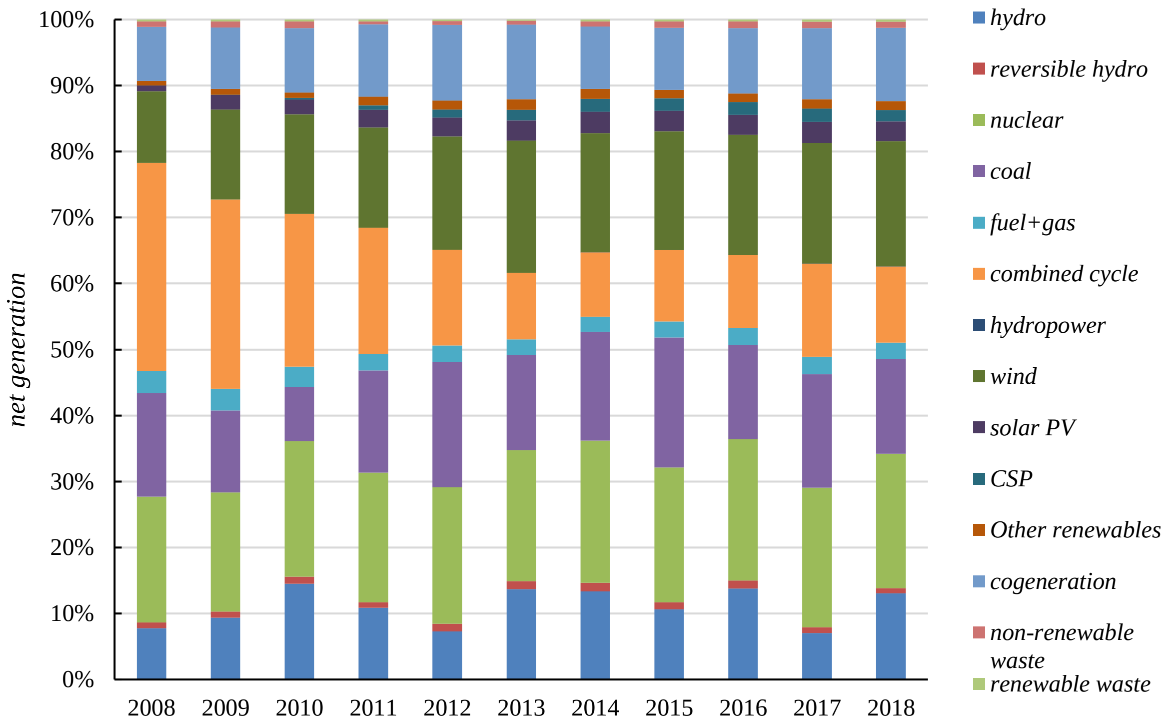


Figure 2.5: Share of the net electricity generation in Spain by technologies in % [6]

California's energy generation tendency follows a similar decreasing tendency as in Spain, although not as pronounced. As we can observe in Figure 2.6, in 2008, the total generation was 209,363 *GWh*, and since then it has been decreasing year by year (except in 2017, where the generation took levels of 2008 – 2009, with 206,387 *GWh*). In 2018 the total generation was 194,727 *GWh* a decrease of 14,636 *GWh*, which equals to 7 *%* decrease in the total generation of the region. It is pretty clear that California has relied on natural gas plants as its main energy source and continues to do so. In 2008, 122,799 *GWh* out of a total of 209,363 *GWh* (58.65 *%*) was produced by Natural Gas plants. Between 2012 and 2014, this percentage grew up to 61 *%*, but in the last few years, due to the increased presence of solar *PV* mainly, this percentage has been reduced to 43.41 *%* in 2017 (89,596 *GWh*) and 46.55 *%* in 2018 (90,642 *GWh*), which remains a pretty high percentage. Nuclear energy produced around 15 *%* of the total generation of the state between 2008 and 2010, with around 32,000 *GWh* per year, with a peak in 2011 with 36.666 *GWh* produced, which translates into 18.21 *%* of the total electricity generation, to drop to an around 9 *%* of the energy produced since 2012, due to the closure of the San Onofre nuclear plant in 2013, due to some minor radioactive vapor leaks in 2012. That 9 *%* of the nuclear energy is produced by Diablo Canyon nuclear plant, which is expected to continue producing energy until the end of 2025, when *PG&E* will stop operating the plant. Geothermal and biomass have remained constant at 6 *%* and 3 *%* of the total electricity generation respectively, which translates to around 12,000 *GWh* produced every year by geothermal energy sources and around 6,000 *GWh* produced by biomass. Solar *PV* has experienced a huge growth in the California region, due to the implementation of politics that encourage the use and improvement of this type of technology. From 2008 to 2011, the energy produced by this type of technology was marginal, with 3 *GWh* produced in 2008, value that increased up to 226 *GWh* in 2011. Since then it has experienced an exponential increase, having produced 24,488 *GWh* in 2018, equivalent to 12.57 *%* of the energy produced.

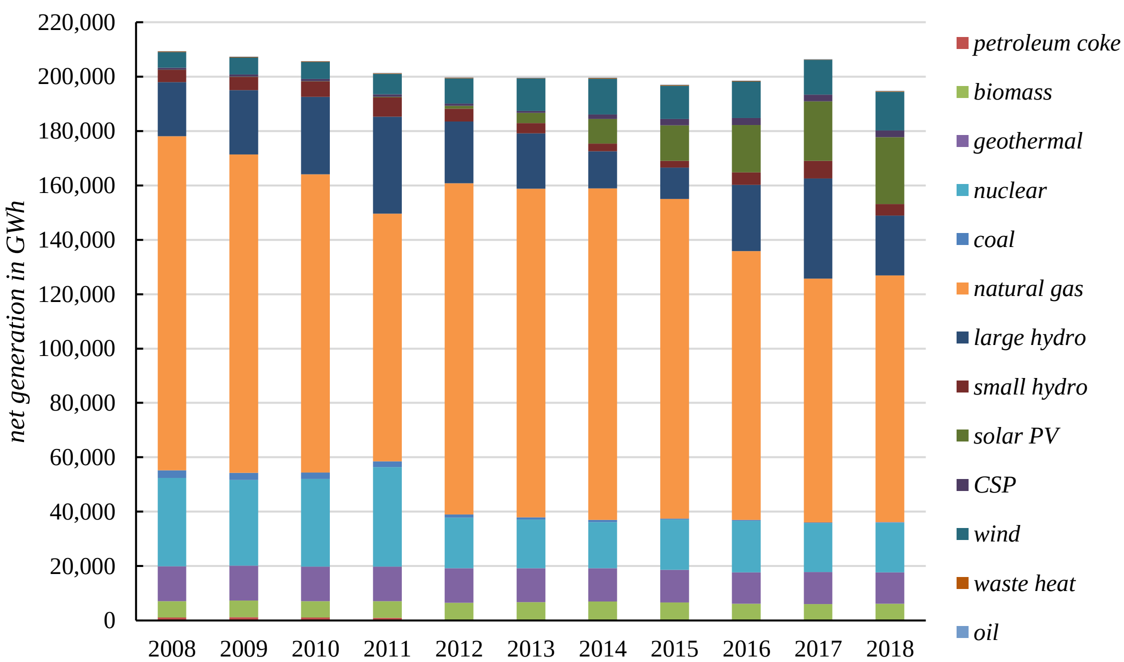


Figure 2.6: Share of the net electricity generation in California by technologies in *GWh* [19-29]

CSP, on the other hand, seemed to have a brighter future with 730 *GWh* of energy produced in 2008. That amount of electricity generated remained constant at around 800 *GWh* per year until 2012, as no new *CSP* plants were connected to the grid. Since 2015, *CSP* plants have been producing around 2,500 *GWh* of energy per year, equivalent to a bit more of 1 *%* of the total electricity produced in the state, so its presence its minor. Wind energy has more than doubled its presence, growing from a 3 % to a 7.31 % of the total electricity generation in 2018, best-ever year with 14,244 *GWh* produced. Its presence in the grid is increasing, although its importance in the grid is still behind the importance wind energy has in Spain's electricity power system. Hydro is the source that most varies from year to year, as its electricity production depends a lot on the weather and amount of precipitation that happen each year. Its electricity production varies for example from 7 % in 2015, to more than 20 % in 2011 and 2017, percentages that include both large and small hydro.

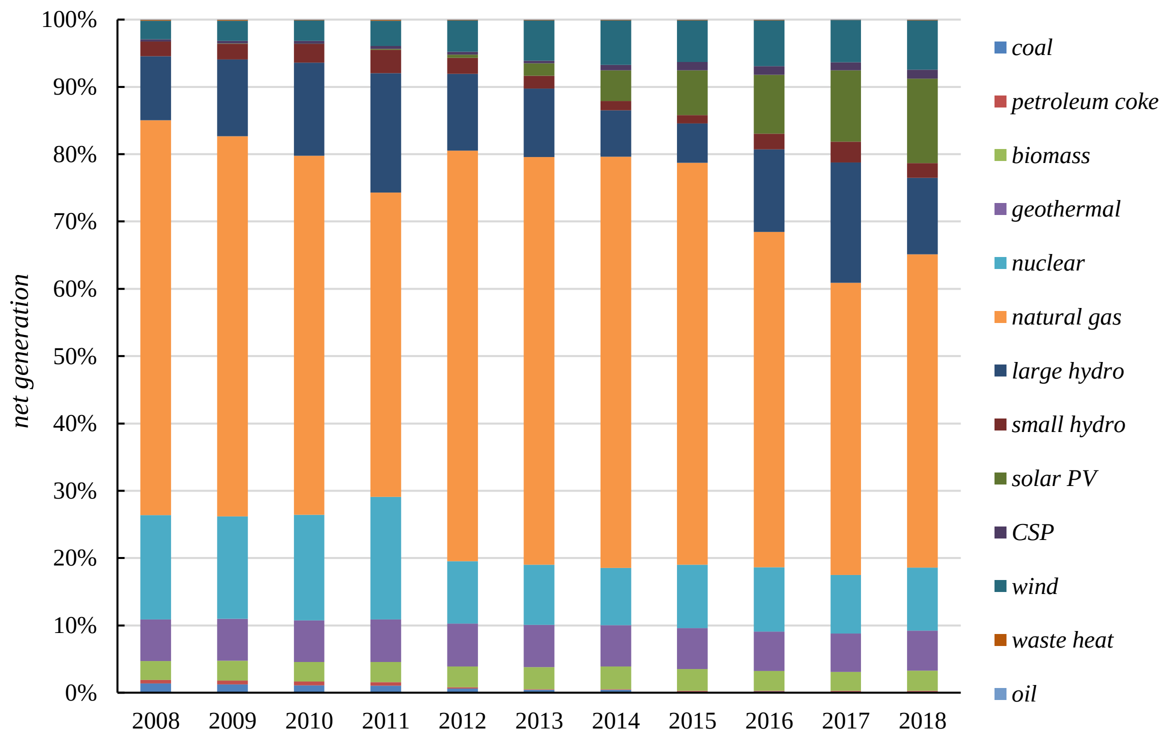


Figure 2.7: Share of the net electricity generation in California by technologies in % [19-29]

In Spain, since 2008, the capacity installed has increased from 94,167 *MW* installed in that year to 108,628 *MW* installed in 2019. of the capacity installed to achieve that 14,461 *MW* difference over the years are from renewable sources. Figures 2.8 and 2.9 show this evolution in the installed capacity. Most By source, these have been the changes. Hydro has stayed practically stable over the years with 16,614 *MW* installed in 2008 to 17,049 *MW* installed in 2018. This little growth is due to that once all hydro power plants have been built, there is no space for building more. Hydro plants make around 16 % of all the capacity installed in Spain. Reversible hydro are those plants that work like normal hydro plants, with the peculiarity and capacity of pumping water back up, being able to generate electricity if waters falls or goes up. There has been 2,451 *MW* installed until 2015 where 878 *MW* were added to the grid, to reach a total of 3,329 *MW*. 3 *%* of the capacity installed in the grid is from this type of technology Nuclear energy has been constant at around 7,500*MW* installed, that decreased to 7,117 *MW* from 2017 onwards. 7 *%* of the installed capacity in the Spanish grid is from nuclear sources. Coal plants are progressively reducing its presence in the grid. 1,295 *MW* have been disconnected from the grid from 2008 to 2019, being 10,030 *MW* the installed capacity in 2019, meaning that a 9 *%* of the installed capacity is from coal energy sources. Fuel+gas plants presence on the grid have been dramatically reduced, from 6,659 *MW*, equal to 7.07 *%* of the grid in 2008 to 2,490 *MW*, equal to 2.39 *%* of the grid in 2018. Combined cycle plants had 22,653 *MW* installed in 2008 and over 26,000 *MW* since 2010, which means that more than 25 *%* of the *MW* installed in the Spanish grid are from this type of technology, being the most popular technology.

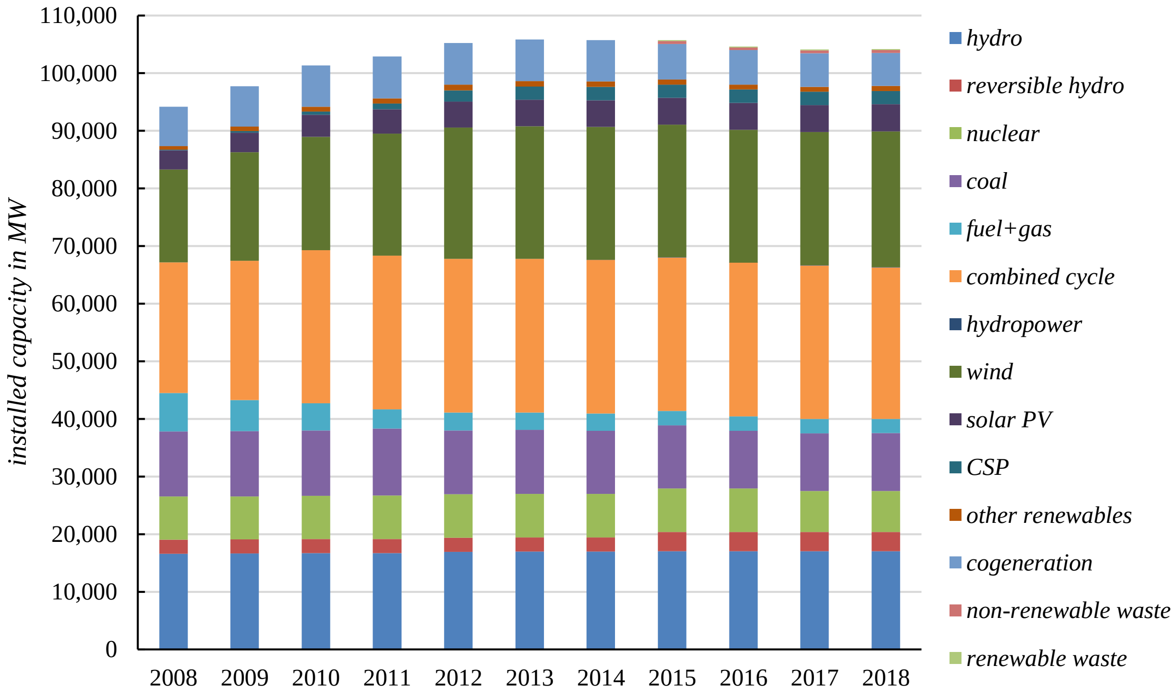


Figure 2.8: Share of the installed capacity in Spain by technologies in *MW* [7]

Hydropower is the name *REE* gives to offshore wind. Its presence its minor, with just only 11 *MW* that were installed in 2014. Wind has experienced a growth of more than 50 *%* in the installed capacity, from 16,133 *MW* in 2008, which was already a 17 *%* of the installed capacity in that year, to 23,589 *MW* installed in 2018, equal to 22.64 *%* of the total installed capacity. Solar *PV* presence in the grid has increased slightly, from 3,351 *MW* in 2008 to 4,714 *MW* at the end of 2018, which means that 4.53 *%* of the installed capacity comes from solar *PV* resources. *CSP* growth was huge, from a minor presence in 2008 with just 61 *MW* installed, it quickly increased to achieve 2,300 *MW* in 2013, but has been constant ath that installed capacity ever since, with no new additions to the grid. Now, only 2 *%* of the installed capacity of the grid comes from *CSP* resources. Other renewables plants capacity installed varies from year to year, without having a fixed development rate. Cogeneration plants had around 7,000 *MW* installed from 2008 to 2014, although the capacity varies slightly from year to year. There was a drop in the installed capacity and now has 5,729 *MW*. Non-renewable waste plants appeared in the grid in 2015 and since then, 500 *MW* of the total installed capacity are from this type of technology. Renewable waste plants had 160 *MW* added in 2015 and have been constant ever since. They have a minor contribution to the grid.

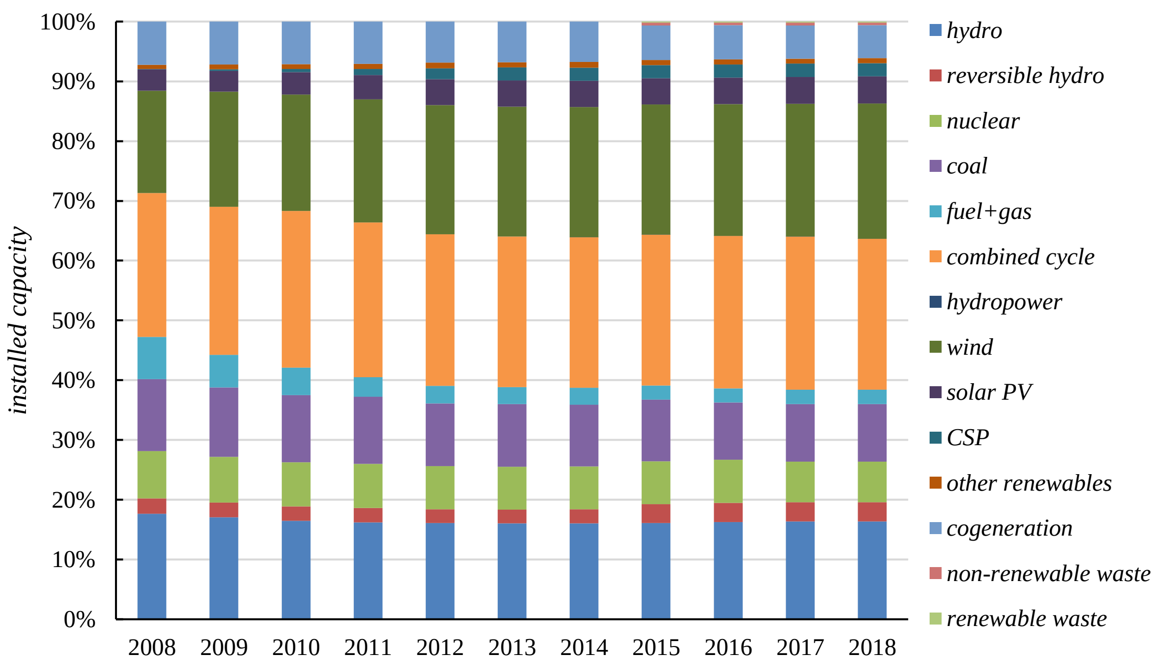


Figure 2.9: Share of the installed capacity in Spain by technologies in *%* [7]

California's grid is "much simpler" than Spain's grid. In Figures 2.10 and 2.11 we can see the evolution of the installed capacity. The installed capacity has increased over the past 12 years, from 67,177 *MW* in 2008 to 80,304 *MW* in 2018. Most of this increase, as it will be seen later, is thanks to the irruption of solar *PV* as other energy source available in the grid. 79,22 *%* of the installed capacity in 2008 were from only two sources, natural gas plants with a 61.25 *%* and large hydro with 17.97 *%*. In 2018, both two mentioned technologies, with the addition of solar *PV*, contribute as well to the 80 *%* of the installed capacity. By technology, this is how the installed capacity has changed. Coal plants had reduced its presence on the grid to being practically inexistent. It reached a peak of 408 *MW* in 2010, but by 2016 only 55 *MW* installed were left, that have been remaining since then. Plants which use petroleum coke followed a similar trend to coal. These plants did not have a lot of presence on the grid with just 173 *MW* back in 2008, that had been reduced to 36 *MW* since 2012.

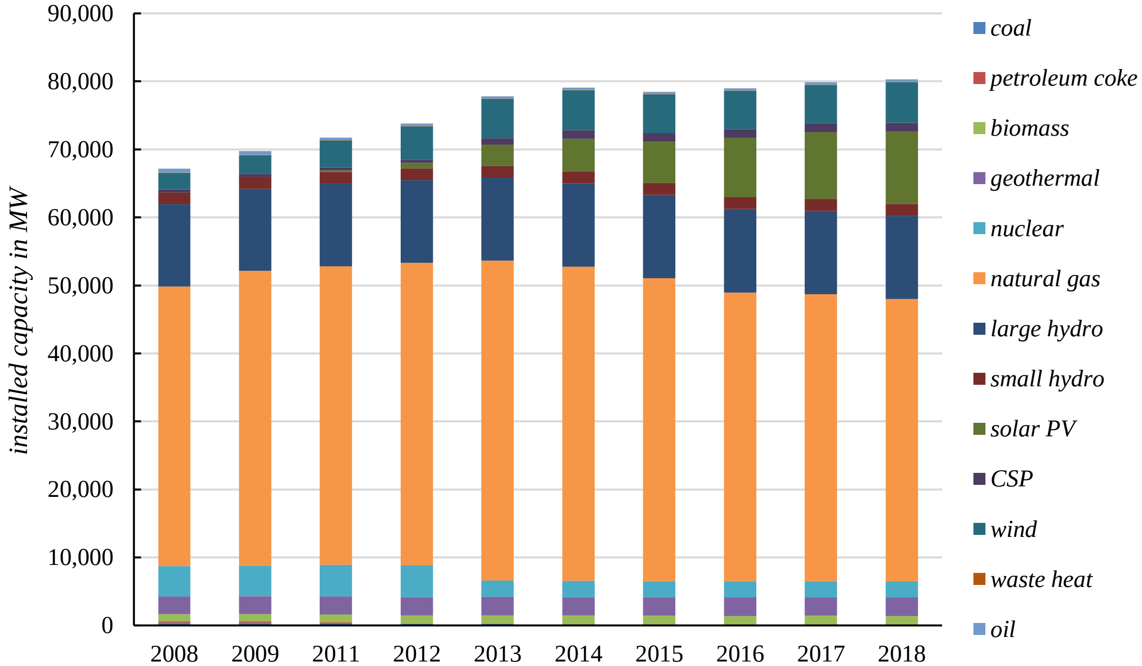


Figure 2.10: Share of the installed capacity in California by technologies in *MW* [30]

Biomass plants have remained more or less constant, with a little increase from 1,084 *MW* in 2008 to nearly 1,300 *MW* in 2018, which represents 1.5 *%* of the of the California grid installed capacity. Geothermal plants have remained stable at 2,600 *MW* during the 2008 – 2018 decade, which means around 3.5 *%* of the installed capacity in the grid. Nuclear plants experienced a drop in the installed capacity in 2012. The amount of *MW* installed to the grid decreased significantly from 4,647 *MW* to 2,393 *MW*, dropping from a 6 *%* to a 3 *%* of the total capacity installed in the grid. Natural gas plants are, without doubt, the main technology used in California's grid. The amount of *MW* connected to the grid is similar in numbers in 2008 and 2018, with 41,149 *MW* and 41,491 *MW* installed respectively, but the amount of *MW* installed increased to 47,084 *MW* in 2013 and has decreased continually since that time. 61.25 *%* of the installed capacity in the grid in 2008 was from this type of technology, and in 2018 is the 51.67 *%*.

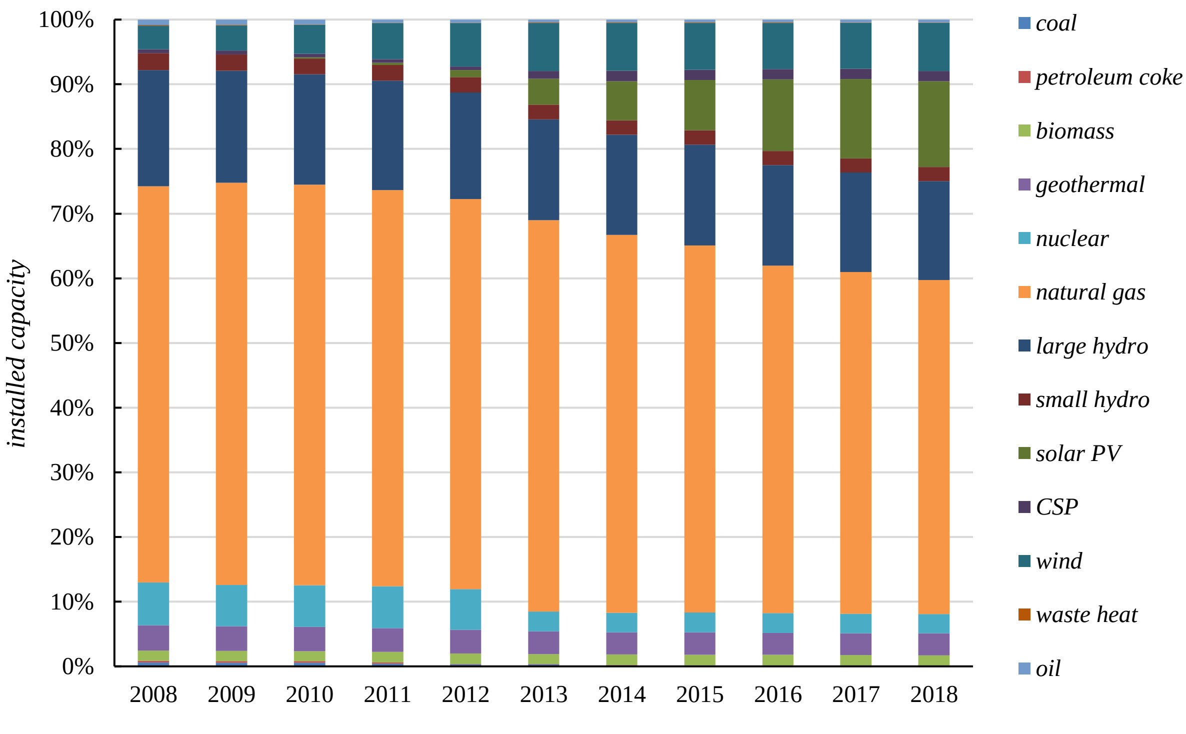


Figure 2.11: Share of the installed capacity in California by technologies in *%* [30]

Large hydro plants have remained constant at around 12,000 *MW* connected to the grid. The same happens in Spain and every place in the world that has achieved its full hydropower potential. Once you have built every hydropower plant, it is very complicated to build more hydropower plants. Small hydro plants have followed the same trend as large hydro, remaining stable at 1,750 *MW* installed to the grid. Solar *PV* growth has been exponential, making California one of the leaders of this type of technology around the world. Its presence was testimonial in 2008, with only 7 *MW* installed. In 2018, that number has grown to 10,658 *MW*, becoming the third technology in terms of capacity installed in California. *CSP* did not follow the same trend as solar *PV*. 400 *MW* had been installed in 2008, and its presence in the grid was tripled by 2015, with 1,249 *MW* connected to the grid ever since. Wind power had 2,462 *MW* of wind power installed in 2008, and in 10 years the amount of *MW* connected to the grid has doubled, reaching 6,004 *MW* in 2018. Waste heat plants have remained constant at 52 *MW* connected to the grid since 2008. Oil plants did not have much presence in 2008 with 575 *MW* connected to the grid, number that had been reduced to the 352 *MW* that are connected in 2018.

2.3. Role of renewables

Both territories are probably one of the greatest exponents of the use of renewable energy today, with clear policies to encourage the use of greener energy. However, the evolution of the use of renewable energy has been quite different over the last decade, as we can see in Figures 2.12 and 2.13.

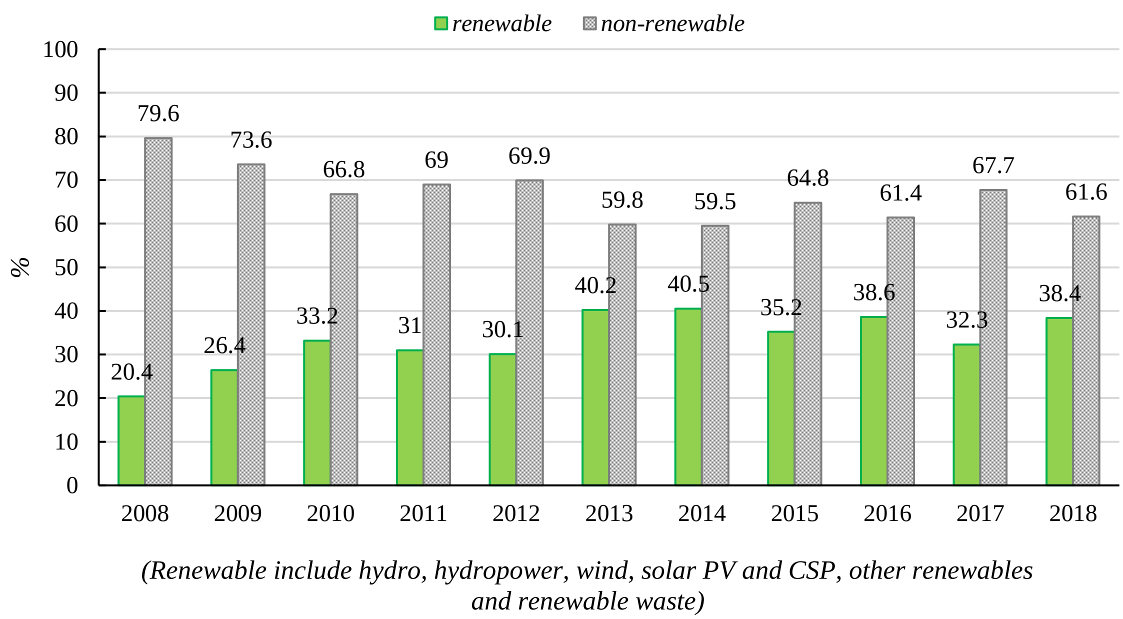


Figure 2.12: Evolution of renewable and non-renewable generation in Spain [31]

Back in 2008, Spain had that the 20.4 % of the total generation of energy was from renewable sources, and has been constant between the 30-40 % of renewable generation since 2010, being above 35 % ever since 2013 (except 2017), and reaching its peak of renewable energy production in 2014 with an impressive 40.5 %.

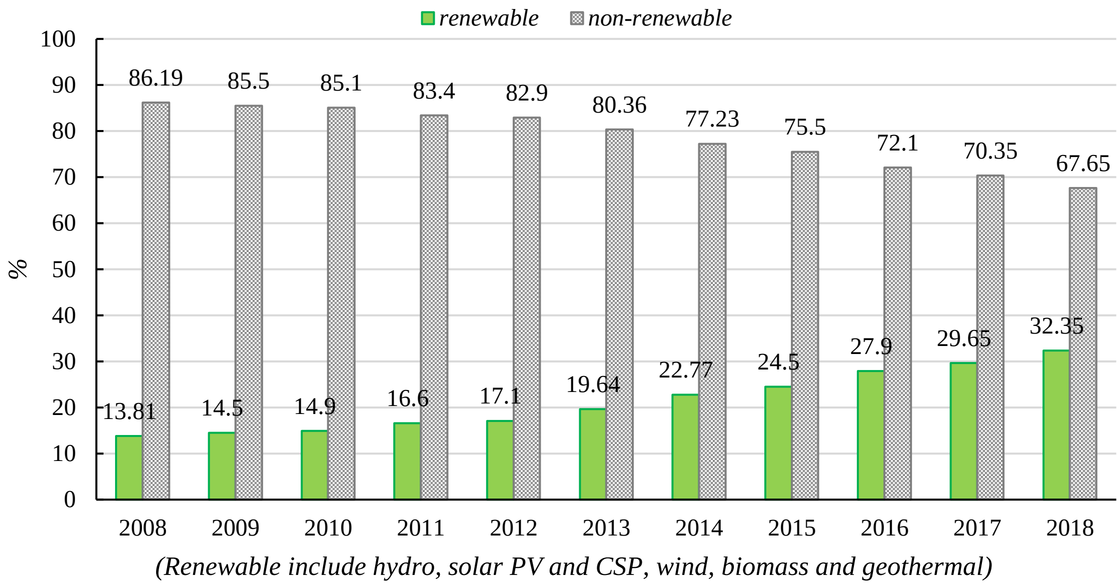


Figure 2.13: Evolution of renewable and non-renewable generation in California [19-29]

On the other side, California has had a constant growth since 2008, increasing year by year it's renewable energy production, from 13.81 % in 2008 to 32.35 % in 2018, a growth of 18.54 %.

2.4. Conclusion

After all that has been analyzed in Chapter 2, we come to the following conclusions. The demand is similar in terms of *GWh* per year on both regions, but while Spain can satisfy its demand just by using its own resources connected to its grid, California has to rely on imports from other states, as it only generates at around 70 % of the total energy the region consumes. Peak loads are decreasing year by year, and it is very unlikely to see peak loads like Spain or California used to have 15 years ago if the energy consumption tendency continues like this. Both regions produce less energy than 10 years ago, but however, the capacity installed to the grid gets bigger. This is because the diversification of the grid. Now we have more different resources, and the new additions to the grid are mainly from renewable sources, which are not in general a 'stable energy source', like nuclear or natural gas plants can be. That is why if wanted to move to greener ways of producing energy, there is a need of having more *MW* installed than before that produce the same amount of energy. California's grid relies basically on 3 technologies nowadays: hydro, natural gas and solar *PV*, which contribute to 80 % of the energy generated. Spain's grid on the other hand is much more diverse and relies on more different technologies. Spain's commitment to renewables has been high over the last decade, with more than 30 % of its energy generation coming from renewable sources uninterruptedly since 2010, reaching peaks of more than 40 % in 2013 and 2014. Wind is its biggest exponent, with nearly 20 % of the total energy produced in the last few years California has done a huge effort of implementing renewable energy resources into the grid, having more than doubled the renewable energy production in just 10 years. This is thanks to the politics that have been applied recently, encouraging green energy sources, especially Solar *PV*.

3. COMPARATIVE ASSESSMENT OF SOLAR RESOURCES IN CALIFORNIA AND SPAIN

Solar Irradiation is a key factor in the efficiency and potential of solar resources. It is easy, the higher the solar irradiation is in one region, the higher the potential of Solar *PV* and *CSP* is in that region, and therefore, the higher is the amount of electricity that can be produced.

But first, it is important to know and differentiate a few concepts regarding solar irradiation. There are 3 important concepts: *DNI, DFI* and *GHI*. [36]

- *DNI* (Direct Normal Irradiance**)** is defined as the amount of solar radiation that is received per unit area on a surface. This surface is always held perpendicular to the rays that come from the sun, so those impact directly the surface. It is measured typically in kWh/m^2. This value has a lot of interest for *CSP* installations and solar *PV* installations that track the position of the sun (1-axis or 2-axis)
- *DFI* (Diffuse Horizontal Irradiance**)** is defined as the amount of solar radiation that is received per unit area on a surface that does not arrive directly from the sun. It has been altered by means and objects from around the surface in question and comes equally distributed from all directions.
- *GHI* (Global Horizontal Irradiance**)** is defined as the total solar radiation that is received per unit area from above by a surface horizontal to the ground. This value has also its importance for photovoltaic installations. *GHI* can be obtained the following way :

$$GHI = DNI * \cos(\alpha) + DHI \quad (3.1)$$

being α the angle between the perpendicular of a surface lying in the ground and the rays from the sun. it is measured as well typically in $kWh/m^2/day$.

3.1. The solar radiation in each region

After having defined what *DNI*, *DFI* and *GHI* are, we can take a look at how those factors appear in the two regions of study. We can look at the maps of Figures 3.1 and 3.2, that were obtained from Solargis [44]. Solargis use a long-term average of *DNI* and *GHI*, with data from 1994 to 2018 in the case of Spain and data from 1999 to 2018 in the case of California, we can extract the following. In Spain, most of the large-scale *CSP* and Solar *PV* projects are located in the regions of Extremadura, Andalucía, Castilla la Mancha and Murcia, all 4 regions located at the south of the peninsula, where solar irradiation is higher. *DNI* takes

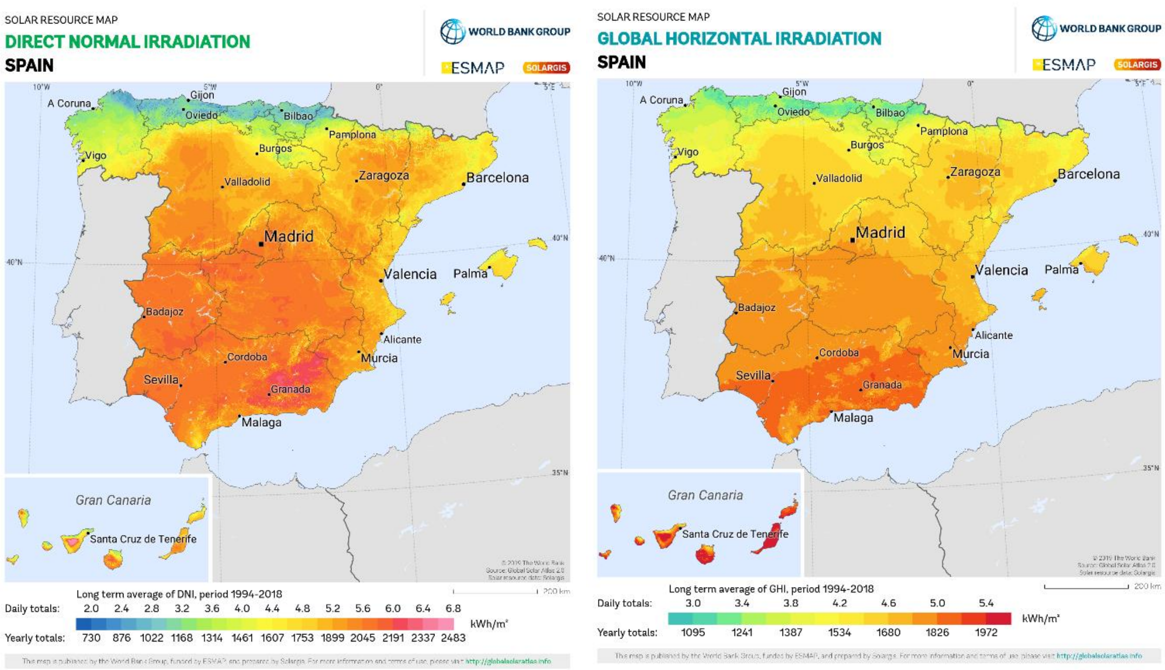


Figure 3.1: Direct Normal Irradiation and Global Horizontal Irradiation in Spain

values of more than 5.4 $kWh/m^2/day$, with more than 6 $kWh/m^2/day$ in the province of Granada. *GHI* takes value of approximately 5 $kWh/m^2/day$ in that same area, value that grows to more than 5.2 $kWh/m^2/day$ in the depression of the Guadalquivir and the province of Granada.

California's large scale *CSP* and *PV* projects are located in the mid and south part of the state, where we can see in the map, the *DNI* and *GHI* take higher values. *DNI* in the area between the cities of Los Angeles, San Diego and the states of Nevada and Arizona takes really high values of more than 7 $kWh/m^2/day$ and reaching more than 8 $kWh/m^2/day$ in some parts, which makes this area suitable to solar projects. *GHI* in this area also achieves greater values than it does in Spain, with values near 6 $kWh/m^2/day$ in all that area.

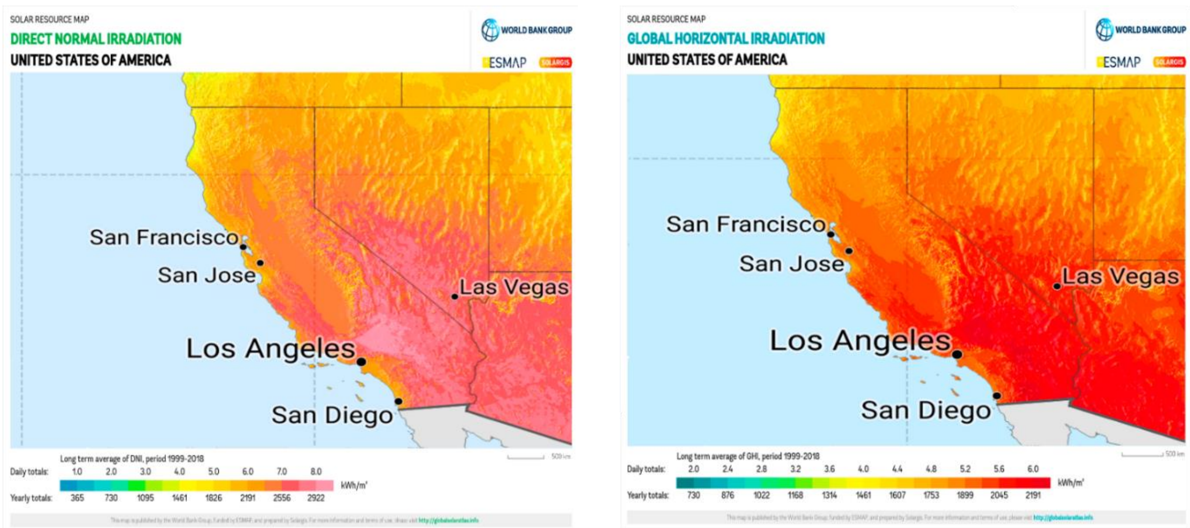


Figure 3.2: Direct Normal Irradiation and Global Horizontal Irradiation in California

3.2. Solar *PV* in California and Spain

A solar *PV* system is a power system that uses sunlight and converts it directly to electricity. It does so by using solar panels, which absorb sunlight and knock electrons loose. These loose electrons flow, creating a DC current, which is transferred through wires to an inverter, which transforms the DC current in AC current, and then normally use a 3-phase transformer to step-up the voltage and connect it to the utility grid.

There are different uses of photovoltaic systems, classified in two main categories: utility-scale and residential or commercial rooftop. We will be focusing more in utility-scale photovoltaic systems in this report.

For utility-scale photovoltaic systems there are different approaches for solar arrays, which differ in efficiency, cost and maintenance cost. A solar array is made from several solar modules, which are interconnected and mounted in structures. [38]

- Fixed arrays: as it name suggests, the mounting structures keep the solar arrays fixed in a single position and orientation, which is previously calculated to provide the best performance possible. As an easy rule, fixed arrays are typically oriented towards the Equator, at a tilt angle similar (usually a little less) a to the latitude of the location chosen. There exist variants of this type of technology which allow the adjustment of the position of the array twice or four times a year, in order to optimize the performance depending on the season of the year.
- Single-axis trackers: Single-axis trackers automatically adjust the position of the solar modules, consistently ‘tracking the sunlight’, throughout the day, increasing energy production compared to fixed arrays by 15-30 *%*. These are the most common tracking systems installed today, as they are more cost-effective and reliable compared to the next type, dual-axis trackers.
- Dual-axis trackers: This last type permits, as well as single-axis, allow the solar modules to track the sunlight, but with two degrees of freedom, which allows them to produce 5-10 *%* more energy than single-axis trackers. To achieve this, they need to be spaced out from each other to reduce inter-shading, so this type of technology requires more land area. Normally, that increase in power efficiency does not outweigh the additional land and *O&M* costs associated.

Solar *PV* in Spain experienced a huge growth in terms of installed capacity in 2008. Most of the large-scale greater than 10 *MW* utility *PV* plants operative nowadays were built and connected to the grid on the second semester of that year, helping improve the total generation from photovoltaic resources the following year 2009. Since then, no big new large-scale utilities have been built, and the growth in the capacity from 2008 to 2012 is thanks to small-scale utility projects and to the installation of photovoltaic panels for residential and commercial use. In 2018, there are only 29 photovoltaic projects with an installed capacity of more than 10 *MW*, contributing to 672 *MW* (14 *%*) of the total photovoltaic installed capacity in the grid.

In Table 3.1, we can see how the total installed solar *PV* capacity is distributed by provinces.

Table 3.1: Installed *PV* capacity per province in Spain (2018)

province	**installed capacity in *MW***	**province**	**installed capacity in *MW***
Andalucia	882	Ceuta	0
Aragón	169	Extremadura	564
Asturias	1	Galicia	17
Baleares	81	La Rioja	86
C. Valenciana	361	Madrid	64
Canarias	167	Melilla	0.1
Cantabria	2	Murcia	442
Castilla La Mancha	925	Navarra	162
Castilla y León	496	Pais Vasco	27
Cataluña	269	total	**4,714**

As mentioned previously, most of the capacity is installed in those areas where *DNI* and *GHI* takes higher values, like Castilla La Mancha, Andalucia, Extremadura, Murcia, Castilla y León and C. Valenciana.

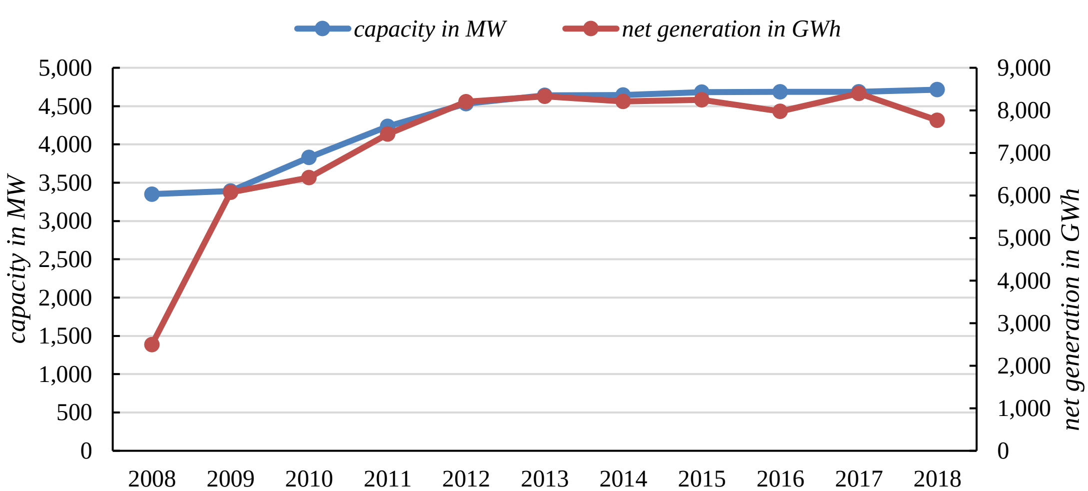


Figure 3.3: Solar *PV* capacity installed and net generation (2008-2018) in Spain

Analyzing Figure 3.3, we can appreciate how the installed capacity increases from 2009 until 2012, to continue almost practically without new additions from 2013 to 2018. The total net generation more than doubles from 2008 to 2009, increasing from the 2,498 *GWh* generated in 2008 to 6072 *GWh* generated in 2009. This increase is thanks to all the new additions to the grid from the end of 2008, which produced energy during all the following year. Since 2009, generation from photovoltaic sources kept growing, and from 2012 to 2018, the generation has been rounding the 8000 *GWh* per year.

Table 3.2: Equivalent hours and *c.f.* values of all solar *PV* plants in Spain

year	**capacity in *MW***	**net generation in *GWh***	**equivalent hours**	***c.f.* in %**
2008	3,351	2,498	745.45	8.51
2009	3,392	6,072	1,790.09	20.43
2010	3,829	6,423	1,677.46	19.15
2011	4,233	7,441	1,757.85	20.07
2012	4,532	8,202	1,809.80	20.66
2013	4,638	8,327	1,795.39	20.50
2014	4,646	8,208	1,766.68	20.17
2015	4,681	8,244	1,761.16	20.10
2016	4,686	7,977	1,702.30	19.43
2017	4,688	8,398	1,791.38	20.45
2018	4,714	7,766	1,647.43	18.81

In Table 3.2, we can see the installed capacity per year, as well as the net generation from each year. We can then obtain the equivalent hours of functioning per year, and therefore the *c.f.* of each year.

As *REE* provides the generation per month per technology, it can be obtained what percentage of the total generation of each month is produced by photovoltaic sources in Spain, as we can see in Figure 3.4.

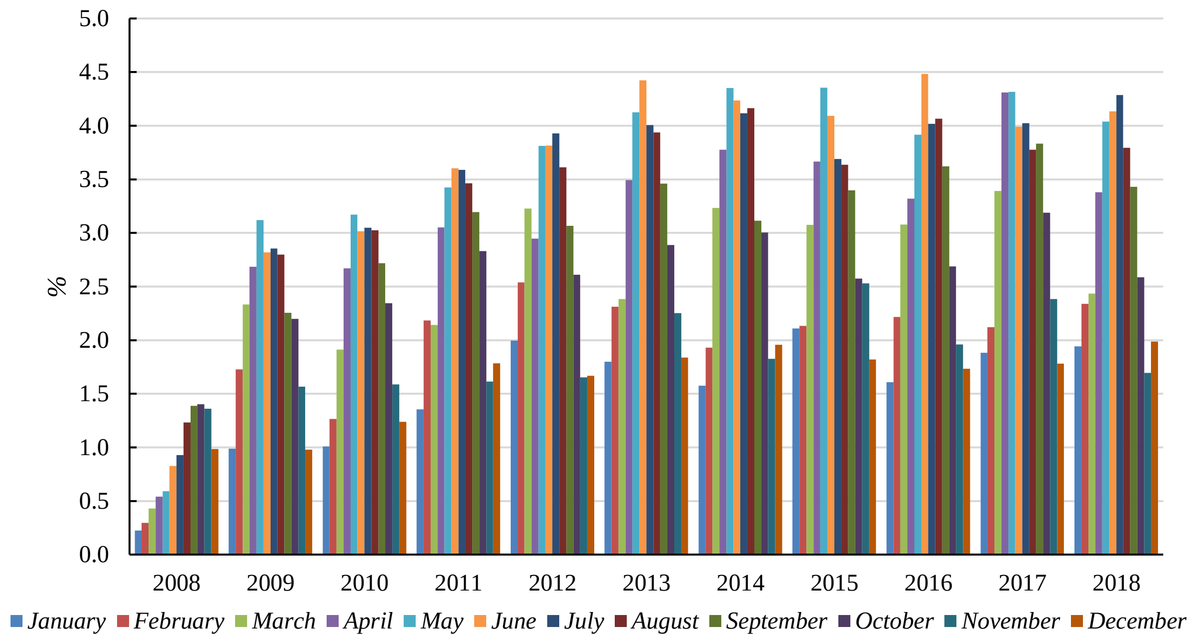


Figure 3.4: Monthly share of total electricity generation in Spain by solar *PV*

The bars corresponding to the year 2008 has a different shape due to the fact that a lot of the installed capacity of that year was connected from September to December. If we focus on the rest of the lines we can see how, as expected, the production is bigger in summer months, reaching peaks of even the 4.5 *%* of the total generation in June 2014, and decreases approximately half in the winter months.

Figure 3.5 provides a better understanding. From 2013 to 2018, the capacity installed to the grid has stayed practically the same, with only 76 *MW* added to the grid in that period, so the potential generation stays practically equal from year to year. Extracting the average for each month for all those years, we can appreciate how between May and July, the contribution to the total generation of the Spanish grid is more than 4 *%*, this value dropping to less than 2 *%* for the winter months of December and January.

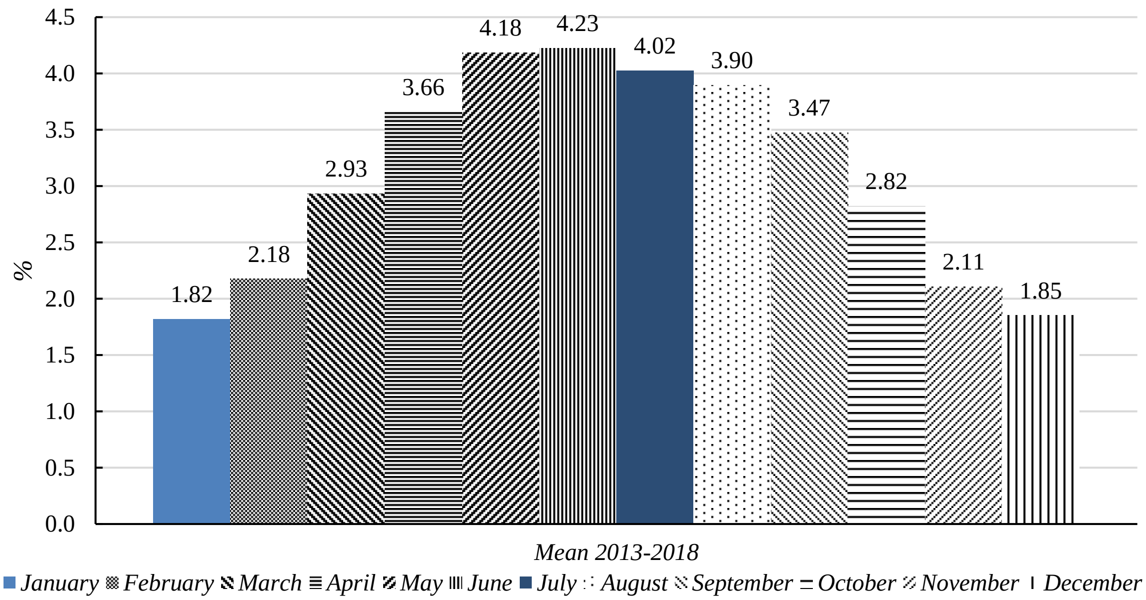


Figure 3.5: Monthly average percentages of the total electricity generation in Spain by solar *PV*

Solar *PV* in California has followed a completely different path than Spain. While in Spain in 2008 there were already 3351 *MW* of capacity installed, in California, as it can be seen in Figure 3.6, there were only 6.8 *MW* that generated only 3.4 *GWh*, which means a *c.f.* of just 5.7 *%*, as we can see in Table 3.3.

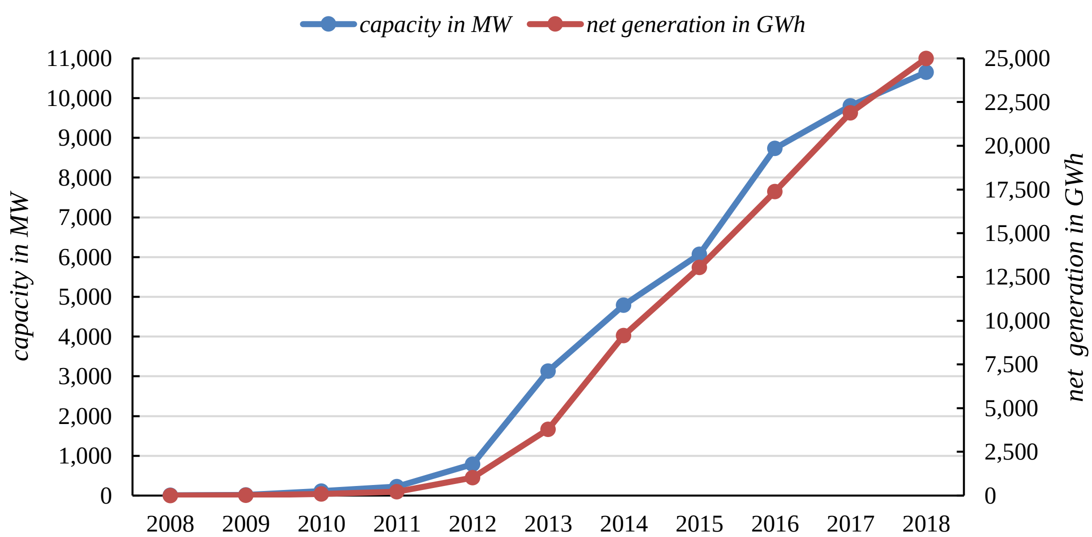


Figure 3.6: Solar PV capacity installed and net generation (2008-2018) in California

The amount of capacity installed increased slowly the following years, reaching 225.8 *MW* installed in 2011. But since 2012 the installed capacity, and therefore the generation, have not stopped growing, until reaching the amount of 10,651.6 *MW* installed in 2018 and almost 25,000 *GWh* generated that year.

Table 3.3: Equivalent hours and *c.f.* values of all solar *PV* plants in California

year	**capacity in *MW***	**net generation in *GWh***	**equivalent hours**	***c.f.* in %**
2008	6.8	3.395	499.26	5.70
2009	13.5	13.89	1,029.19	11.75
2010	115	86.91	755.71	8.63
2011	225.8	223.17	988.36	11.28
2012	791.6	1,022.26	1,291.38	14.74
2013	3,129.1	3,792.53	1,212.02	13.84
2014	4,788.8	9,143.06	1,909.26	21.80
2015	6,073.5	1,305.32	2.148.73	24.53
2016	8,738.9	17,377.95	1,988.57	22.70
2017	9,806.1	21,887.88	2,232.07	25.48
2018	10,651.6	24,995.73	2,346.66	26.79

With the data from Table 3.3 above, we can appreciate that the general *c.f.* is higher than in Spain. However, there is a very significative data on how solar *PV* energy is approached differently. While in Spain in 2018, only the 10.6 *%* of the installed capacity came from utilities bigger or equal to 20 *MW*, in California the *%* of installed capacity that comes from utilities greater than 20 *MW* is of the 84.3 *%*. While Spain has only 17 projects of these characteristics in 2018, in California the number is 140. There is also a big difference in the size of the utilities. Spain´s biggest photovoltaic plant is “Parque Fotovoltaico Puertollano”, with an installed capacity of 70 *MW*. Meanwhile, California has 31 projects larger than 100 *MW*, being “Topaz Solar Farms LLC”, with an installed capacity of 550 *MW*, the biggest of them all.

In Figure 3.7, we analyze all the *c.f.* values of all solar *PV* projects with an installed capacity higher than 20 *MW* in California. We can see how the performance has improved since 2016.

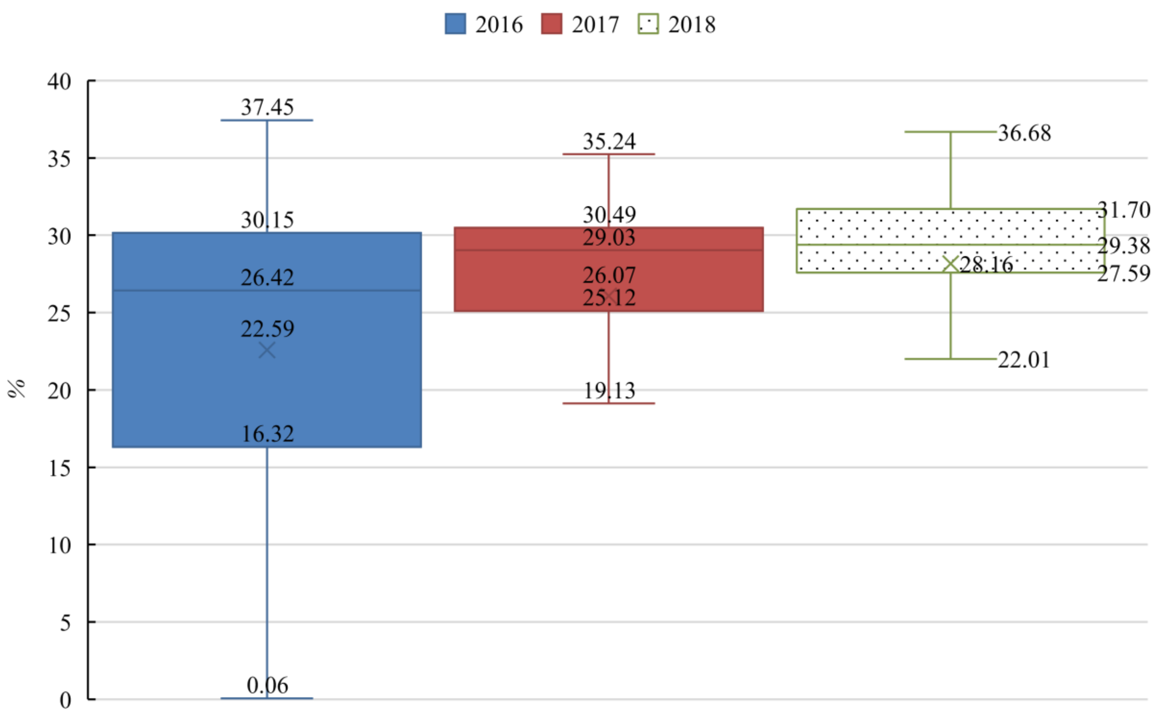


Figure 3.7: Range of *c.f.* values of California solar *PV* plants greater than 20 *MW*

In 2016, California had 112 projects operative. In 2017, that number increased to 132 projects, which continued to increase in 2018 to reach 140 total projects. In 2016, the average *c.f.* was 22.59 *%*. The median was 26.42 %, while the quartile 1 was 16.32 % and quartile 3 was 30.06 %. The first quarter of all the projects performed in the [0.06, 16.32] *%* range, the second quarter performed in the [16.32, 26.42] *%* range, the third quarter in the [26.42, 30.06] *%* range, and the last 25 *%* in the [30.06, 37.45] *%* range. The 37.45 *%* is the highest *c.f.* achieved by a *PV* plant during those years, achieved by 'Seville Solar One' a plant of 20 *MW* that generated 65,604 *MW*h. In 2017 the average *c.f.* increased up to 26.07 *%*. The overall performance increased as well, with only 7 outsiders that performed under 19.13 *%*. 50 *%* of the projects had a *c.f.* value in the [29.03, 35.24] *%* range. The 35.24 *% c.f.* was achieved again by 'Seville Solar One', which produced 61,732 *MW*h that year, equivalent to 3,086.6 hours. In 2018, the mean was 28.26 *%*, which continues to be a higher value than the previous year. The overall performance increased as well, with only 7 outsiders. The rest of the projects performed with a *c.f.* value in the [22.01,36.68] *%* range, with the median at 29.38 *%*, and having 25 *%* of the projects with a *c.f.* value of more than 31 *%*, a relatively high value for *PV* plants. "RE Mustang", a 30 *MW PV* plant produced 96,407 *MWh*, equivalent to 3,213.6 hours and a *c.f.* value of 36.68 *%*.

3.3. *CSP* in California and Spain

CSP use the heat of sunlight as the source to produce energy, unlike photovoltaic panels, which directly convert the sunlight into electricity. *CSP* technologies use different kind of mirror configurations to concentrate the light of the sun in one point and produce heat. This heat is then used to produce steam, and this steam is used afterwards to spin a turbine and produce electricity. *CSP* plants can also integrate thermal energy storage systems, normally using molten salts or synthetic oils, which are stored at a high temperature in insulated tanks. The heat from the molten salts or synthetic oil can be afterwards used to create steam and produce electricity. The use of thermal storage makes the energy dispatchable, so it can be delivered to the grid at times where there is no sunlight. [37]

There 4 different types of *CSP* technology: solar power tower, parabolic trough, concentrating linear fresnel reflector and stirling dish. The two most common are parabolic trough and solar power tower, while the use of the fresnel reflector and dish is minor.

- ❖ Parabolic trough: it consists of a series of linear parabolic reflectors, trough-shaped, which concentrate the sun's energy onto a receiver pipe that is positioned along the reflector's focal line. This reflector tracks the sun during daytime, so the reflection of sunlight is always pointing at the receiver pipe. Inside this pipe there is a working fluid, normally thermal oil, whose temperature is increased from 293 ºC to 393 ºC. The heat energy is then used to generate steam and generate electricity. The first *CSP* plants were the Solar Energy Generating Systems (*SEGS*), built from 1984 (*SEGS* I) until 1990 (*SEGS* IX), use this type of technology. Europe's first *CSP* plant, Andasol-1 was built in the province of Granada (Spain), and uses this type of technology. In 2018, 90 *%* of all *CSP* plants around the world use parabolic trough technology.
- ❖ Solar power tower: this technology uses dual axis tracking mirrors, which are called heliostats, to concentrate sunlight in a point situated at the top of a central receiver atop (tower). At the top of this tower there is a heat-transfer fluid, heated up to nearly 600 ºC water-steam or molten salts. The earliest power tower projects used steam

directly to produce energy, but because of the use of steam, they were unable to use thermal storage. But with the use of molten salts, thanks to having a superior heat transfer and storage capacity, thermal storage can be used. Ivanpah Solar Power Facility in California, with 392 *MW*, has 3 different towers, and operates commercially by converting water to steam directly. Planta Solar 10 (PS10) located in Sanlucar la Mayor, Spain, was the first utility-scale plant to use this type of technology.

- ❖ Fresnel reflectors: they use a similar concept to parabolic trough. They use thin, flat mirrors, which are located in parallel rows and reflect the sunlight to the pipes above, where there is a working fluid that is heated, just like parabolic troughs do.
- ❖ Stirling dish: it consists on a stand-alone, parabolic-shaped reflector that concentrates sunlight in one receiver point that is positioned at the focal point. Dishes are built in a structure with a two-axis tracking system that allows to track the light of the sun.

The current distribution of all the *CSP* projects around the projects, as well as the total capacity per country can be seen in Figure 3.8 below.

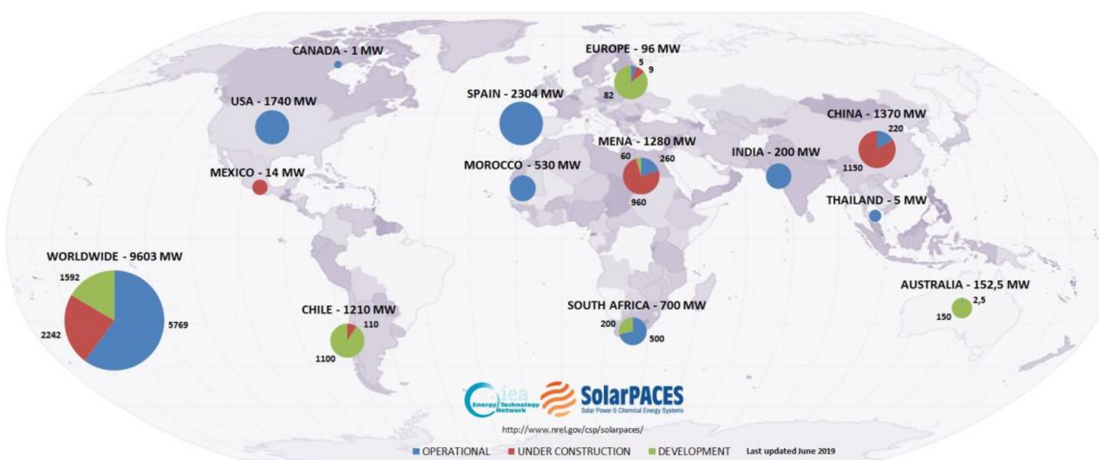


Figure 3.8: *CSP* capacity installed per country [33]

There is a total of 9,063 *MW* of installed power distributed the following way: 5,769 *MW* are operational projects; 2,242 *MW* are currently under construction while there are 1,592 *MW* in future development status. Spain is undoubtedly the leader around the world of this type of technology. In 2018, it had 2304 *MW* of installed capacity, almost 40 % of all the capacity installed around the world. As we can see in Figure 3.9, those 2304 *MW* were installed quickly between the years of 2008 and 2013. In 2008, Spain only had 61 *MW* connected to the grid, which produced just 15 *GWh*, equivalent to a *c.f.* of just 2.8 *%*. Some new projects were being created year by year until 2013, when Spain reached a total number of 50 projects, the vast majority of them 50 *MW* parabolic trough plants, with just 3 solar power tower plants with powers of 20 *MW* and 10 *MW*, and 2 Linear Fresnel Reflectors, one of them of 30 *MW*. Out of the 50 projects, 24 count with thermal storage.

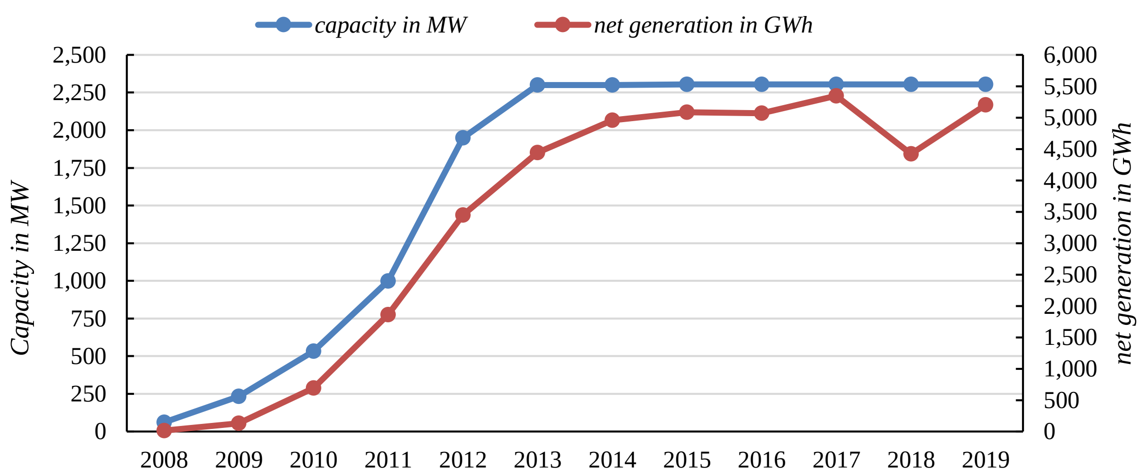


Figure 3.9: *CSP* capacity installed and net generation from 2008 to 2018 in Spain

Table 3.4: Equivalent hours and *c.f.* values of all *CSP* plants in Spain

year	**capacity in *MW***	**net generation in *GWh***	**equivalent hours**	***c.f.* in %**
2008	61	15	245.90	2.81
2009	232	130	560.34	6.40
2010	532	692	1,300.75	14.85
2011	999	1,862	1,863.86	21.28
2012	1,950	3,447	1,767.69	20.18
2013	2,299	4,442	1,932.14	22.06
2014	2,299	4,959	2,157.02	24.62
2015	2,304	5,085	2,207.03	25.19
2016	2,304	5,071	2,200.95	25.13
2017	2,304	5,348	2,321.18	26.50
2018	2,304	4,424	1,920.14	21.92

Above in Table 3.4 we can see the net generation in *GWh* per year. Since 2013, the capacity installed has not changed, and the general *c.f.* of all the *CSP* plants has been increasing, except in 2018, where it dropped from 26.50 *%* to 21.92 *%*, due to a considerable decrease in generation, from 5348 *GWh* to 4424 *GWh*. In Figure 3.10, as *REE* provides the data for the generation of each month of every type of technology included in the grid, we can obtain for each year, the percentage of total generation of every month.

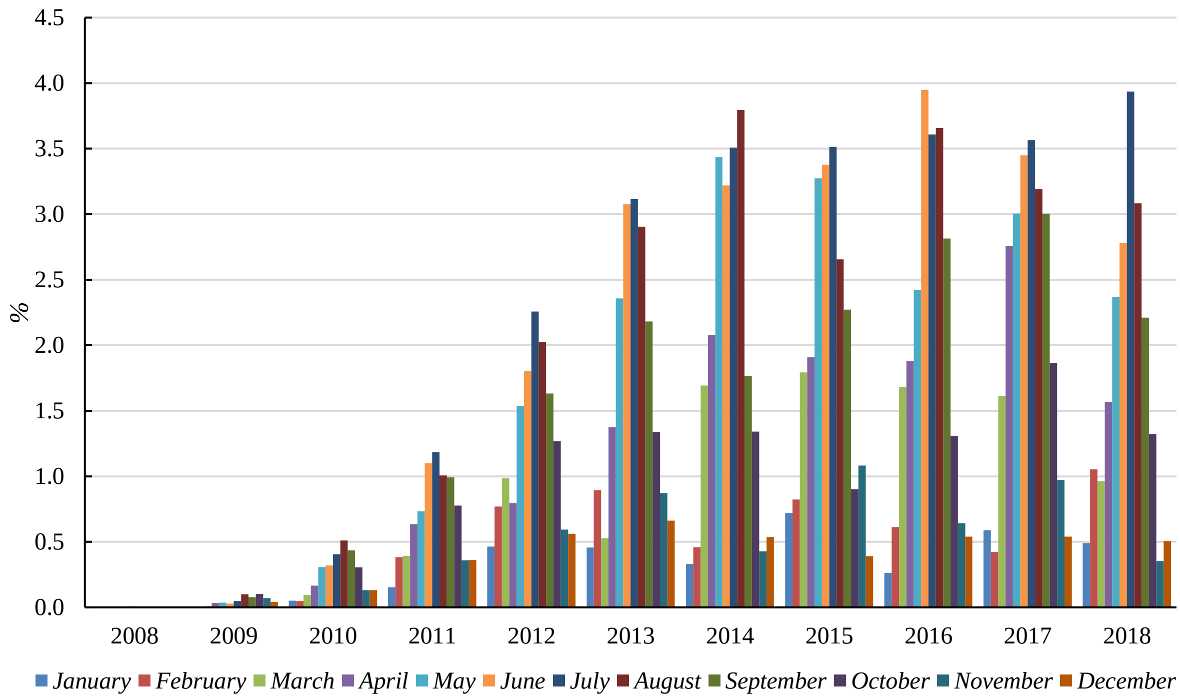


Figure 3.10: Monthly share of total Spanish electricity generation by *CSP*

As we can see in Figure 3.10, for the years 2008 and 2009, the share of the total generation was minor, as the capacity installed to the grid was low. Then, as capacity installed started to increase, the percentage out of the total generation starts to grow as well. In 2010, in August a 0.51 *%* is reached. In 2011 in July a 1.19 *%* of the total generation, while in 2012, 2.26 *%* of the total electricity generation of Spain is reached in July again.

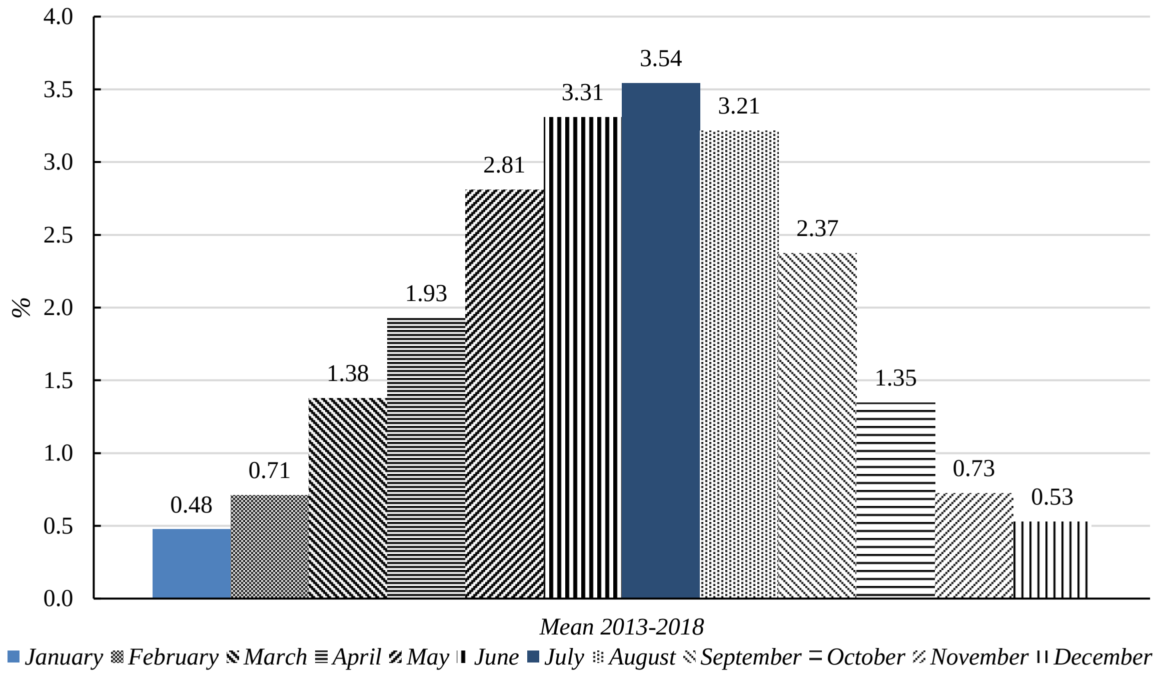


Figure 3.11: Monthly average percentages of the total electricity generation in Spain by *CSP*

From 2013 until 2018, as the installed capacity did not change, the mean of each month is calculated from the data of those years, stablishing the following curve. As we can see In Figure 3.11, the performance varies dramatically between summer months and winter months. In June, July and August, percentages bigger than 3 % are achieved. This percentage drops more than 6 times in months like December or January, were only values around the 0.5 % out of the total generation in Spain are achieved.

California was the pioneer of this type of technology, with the Solar Electric Generating Stations (*SEGS*), 9 plants that used the parabolic trough technology. The first one (*SEGS* I) was a 13.8 *MW* plant built in 1984, while *SEGS* II was built in 1985 increasing the capacity to 33 *MW*. Both plants are located in Dagget, but they are not operative nowadays. In 1985 *SEGS* III, a 33 *MW* plant was built as well, located in Kramer Junction. In that same location is were *SEGS* IV to *SEGS* VII were built in 1989, while the two last plants were built between 1989 and 1990 in Harper Dry lake. *SEGS* VIII and *SEGS* IX had their capacity increased up to 92 *MW*.

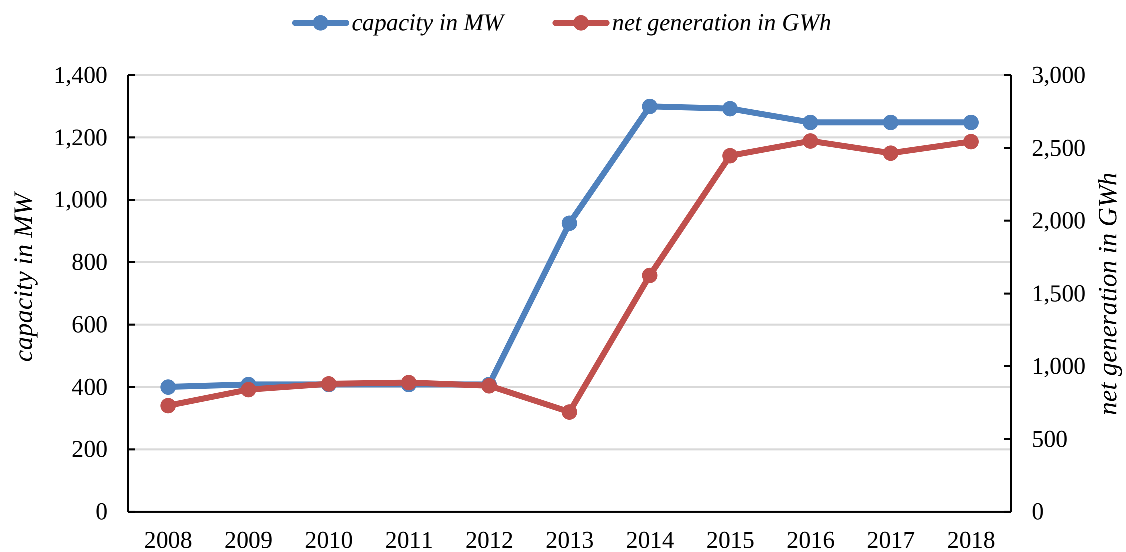


Figure 3.12: *CSP* capacity installed and net generation from 2008 to 2018 in California

As well, other bigger projects have been built, with high-capacities like the Mojave Solar Projects, a 250-*MW* parabolic trough plant located in Harper Dry Lake or the Genesis Solar Energy Project, another 250-*MW* parabolic trough plant located in Blythe. As well, the biggest solar power plant was built in 2014, the Ivanpah Solar Electric Generating System (I*SEGS*), with its 3 towers and a total of 392 *MW*. Unfortunately, none of the projects have the capacity of using thermal storage, 'wasting' one of the main advantages that *CSP* power plants offer. Currently (if we consider Ivanpah as being 3 different projects, one for each solar power tower) there are 12 operative projects in California.

In Table 3.5 we can observe the evolution from 2008 to 2018. Until 2012 there were about 400 *MW* of installed capacity, which coincides to the sum of the capacity of the *SEGS* plants plus some marginal projects. We can observe how the equivalent hours of functioning was above 2,000 hours per year, with general *c.f.* values of over 24 *%*. In 2013, although there were additions to the grid, the generation dropped from 866.94 *GWh* in 2012 to 685.85 *GWh* that year. In 2014, it reached its maximum capacity connected to the grid with almost 1300 *MW*. From 2015 to 2018 the generation was constant at around 2500 *GWh* generated per year, with a *c.f.* between 22-23 *%*.

Table 3.5: Equivalent hours and *c.f.* values of all *CSP* plants in California

year	**capacity in *MW***	**net generation in *GWh***	**equivalent hours**	***c.f.* in %**
2008	400,4	730.152	1,823.56	20.82
2009	407,9	840.52	2,060.60	23.52
2010	407,9	878.835	2,154.54	24.60
2011	407,9	888.843	2,179.07	24.88
2012	407,9	866.941	2,125.38	24.26
2013	924,9	685.849	741.54	8.47
2014	1,299,9	1,623,568	1,248.99	14.26
2015	1,292,4	2,446.285	1,892.82	21.61
2016	1,248,6	2,548.09	2,040.76	23.30
2017	1,248,6	2,463.598	1,973.09	22.52
2018	1,248,6	2,544.616	2,037.98	23.26

The California Energy Commission [48] provides data of the electricity generated per facility per year, which allows us to take a deeper look on how each plant performances and the set of plants altogether. Figure 3.13 shows a boxplot of with the range of capacity factors from the years 2016 to 2018.The year 2016 shows the better general performance. All plants performed above a *c.f.* of 16 *%*, being the average 20.66 *%*. A *c.f.* of 28.95 *%* was achieved by the Genesis Solar Energy Plant. In 2017, the performance dropped in general terms. The average *c.f.* dropped from 20.66 to 19.22 *%*. A quarter of the *CSP* plants had a *c.f.* between 14.21 *%* and 14.70 *%*. In 2018, the boxplot **s**hows more dispersion than the previous years. The average grows a little bit, going from 19.22 *%* to 19.63 *%*. The same happens with the median, going from 18.33 to 18.71 *%*. However, *SEGS* VII *c.f.* value was only 12.94 *%*, being the lowest *c.f.* from the 3 years we have studied.

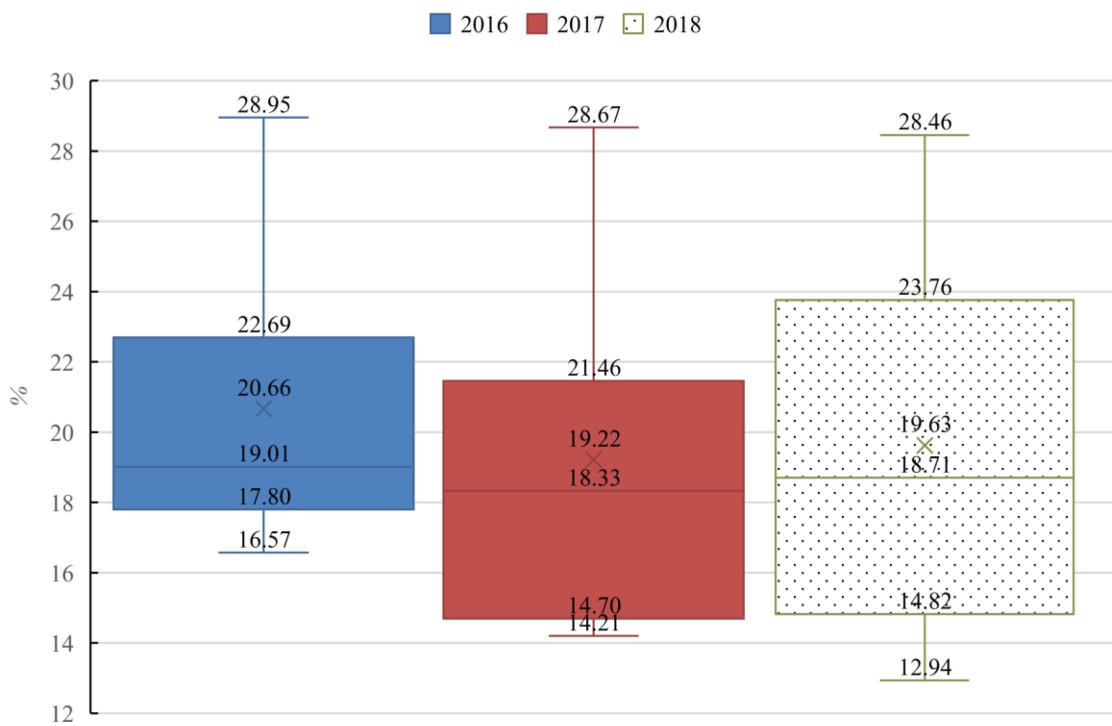


Figure 3.13: Ranges of *c.f.* values of *CSP* plants in California

We can appreciate looking at Table 3.6 that the difference in performance between the old plants and the new ones is considerable. While the plants built in 1985-1990, do not achieve *c.f.* values of over 20 %, that is not the case for the plants that were built in 2014. As well, the difference in performance between the plants of Genesis Solar Energy Project and Mojave Solar Project, which use parabolic trough technology, and the Ivanpah Solar Electric Generating System, which uses solar power tower, is considerably significant.

Table 3.6: *c.f.* (2016-2018) of *CSP* projects in California

		***c.f.* in %**		
plant name	**year built**	**2016**	**2017**	**2018**
Genesis Solar Energy Project	2014	28,95	28,67	28,46
Ivanpah I (Solar Partners II)	2014	23,17	21,64	21,96
Ivanpah II (Solar Partners I)	2014	17,16	20,33	23,78
Ivanpah III (Solar Partners VIII)	2014	21,26	20,92	23,72
Mojave Solar Project	2014	28,53	27,09	27,62
SEGS III	1985	18,60	14,21	14,83
SEGS IV	1989	18,43	14,60	14,82
SEGS V	1989	18,64	17,24	15,82
SEGS VI	1989	16,57	14,97	14,16
SEGS VII	1989	17,59	14,26	12,94
SEGS VIII	1989	19,39	17,84	18,40
SEGS IX	1990	19,60	18,82	19,02

3.4. Conclusion

After analyzing the solar irradiation from both regions and the status and performance of solar *PV* and *CSP*, we can extract the following conclusions. Direct Normal Irradiation (*DNI*), which is a very influential factor for *CSP* Projects, and Global Horizontal Irradiation (*GHI*), important for photovoltaic installations take higher values in California, so in theory, the performance of the plants in California should be higher. The investment in solar *PV* in Spain has been stuck since 2012 at around 4600 *MW* of installed capacity, which means only 4.5 *%* of the capacity installed in the grid and a 3 *%* of the total generation in a year. That contrasts heavily on how solar *PV* has improved in California. From being a marginal technology in 2008 and 2009, the investment has been huge and in 2018, 13.27 *%* of the installed capacity in California and the 12.58 *%* of the total generation comes from solar *PV* resources, making it the 3rd most spread technology in California's grid. *CSP* in Spain has a similar situation that solar *PV* in Spain. Spain was the precursor of this kind of technology in Europe and become the leader around the world of this type of technology reaching an installed capacity of 2300 *MW* in 2012, with 50 different projects in operation. It still maintains leader position, with almost 40 *%* of the total capacity installed around the world, but the situation has been stuck since then, with no new projects. If Spain was the precursor in Europe, is legitimate to say that California, with it *SEGS* plants, was the precursor around the world in 1984. There was a blank in new additions to the grid from this technology until 2014, when 3 big projects were built (capacities of 250 *MW*, 250 *MW* and 392 *MW*). Since then, as well as in Spain, the situation has been stuck. A symptomatic fact of the moment *CSP* projects are living is that *SEGS* I and II, parabolic trough plants, have been transformed into *PV* plants. One of the main claimed advantages of *CSP* projects is the possibility of using thermal storage, which makes energy dispatchable when necessary. However, none of the projects in California have storage available, and only 24 out of 50 projects in Spain take advantage of this characteristic. Performance on *PV* solar in California is better than in Spain, achieving really high *c.f.* values. In Spain, only 10 *%* of the installed *PV* capacity comes from large-scale utility projects greater than 20 *MW* number that grows to 14 *%* if we consider the projects larger than 10 *MW*. In California, 84 *%* of the installed capacity comes from projects with an installed capacity higher than 20 *MW*. The approach towards *PV* technology is completely different. The general *c.f.* of solar *PV* projects in Spain varies around 20 *%*, while in California that value increases considerably to numbers up to 25-26 *%*. 25 *%* of the projects in 2018 achieved *c.f.* over 31 *%*, while the vast majority, almost 100 *%* of the 140 projects in California, had *c.f.* over 22 *%*, 2 *%* more than the general *c.f.* of the plants in Spain. The general *c.f.* in Spain of *CSP* plants was 6 *%* higher compared to *PV* Plants. This could have a relation with the use of thermal storage that is available in 24 *CSP* projects. The opposite happens in California. *CSP* plants performance is worse than *PV* plants performance. To compare, we can take a look at Table 3.7.

Table 3.7: Best *c.f.* values of projects in California per technology

	year		
technology	2016	2017	2018
CSP best *c.f.*	28.95	28.67	28.46
PV best *c.f.*	37.45	35.24	36.68

4. ENVIRONMENTAL CHARACTERISITICS OF THE ELECTRICITY SECTORS IN CALIFORNIA AND SPAIN

Since the start of the First Industrial Revolution and, particularly, more significantly after the Second Industrial Revolution, the level of manufacturing and production of goods around the globe has grown markedly, increasing with it the human activities that are associated with CO_2 and various other emissions. As we well know, this drastic increase in the CO_2 emissions has relevant consequences, starting with global warming and all the consequences that they entail, including the steady raise of the mean global temperature, continued ice melting at the poles and a marked increase in the sea level. Recent years have seen initiatives aimed to reduce the volume of emissions that each nation emits into the atmosphere, such as the Kyoto Protocol and the Paris Agreement. The Kyoto Protocol specified targets to limit and reduce *GHG* emissions in industrialized countries, setting up targets (5 % average annual reduction compared to 1990 between 2008-2012, increased to 18 % average annual reduction between 2013-2020 compared to 1990 levels). The Paris Agreement continues the battle against climate change with the goal to keep the global temperature below 2 Celsius degrees above pre-industrial levels and pursue efforts to limit this raise in temperature at 1.5 Celsius degrees.

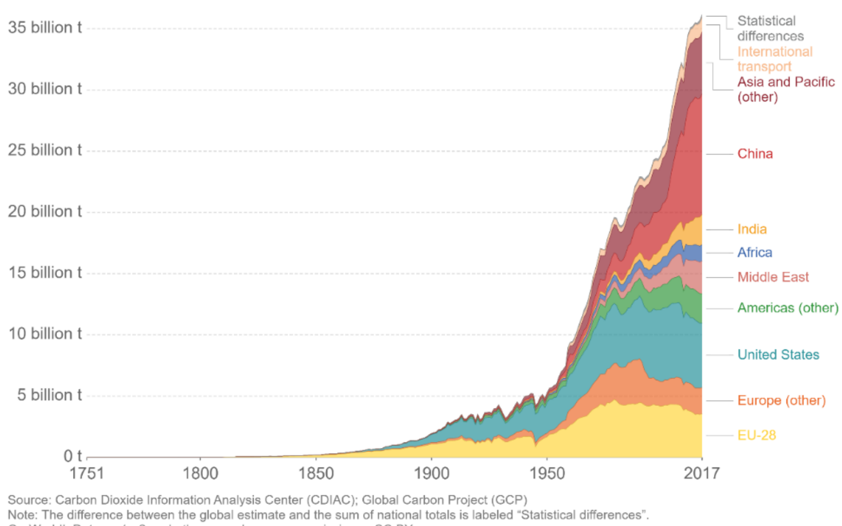


Figure 4.1: CO_2 world emissions (1751-2017). Source: IRENA [35]

Figure 4.1 illustrates how this CO_2 emissions have increased and is clearly visible how the global annual volume of CO_2 emissions has increased a seven-fold since 1950. The rapid industrial development of China, India and other countries in South East Asia has contributed heavily in the increase of annual CO_2 emissions around the globe, while the CO_2 emissions in the US and Europe have stayed approximately constant since the 1980's.

Figure 4.3 illustrates better how much CO_2 emissions have increased since 1990. The total amount of CO_2 emissions has increased in a 62.44% in 28 years. However, we can appreciate how the reason of this growth is thanks to the emissions increasing in the rest of the world, as mentioned before, with China leading this ranking with 27.2% of all the CO_2 emissions in 2018.

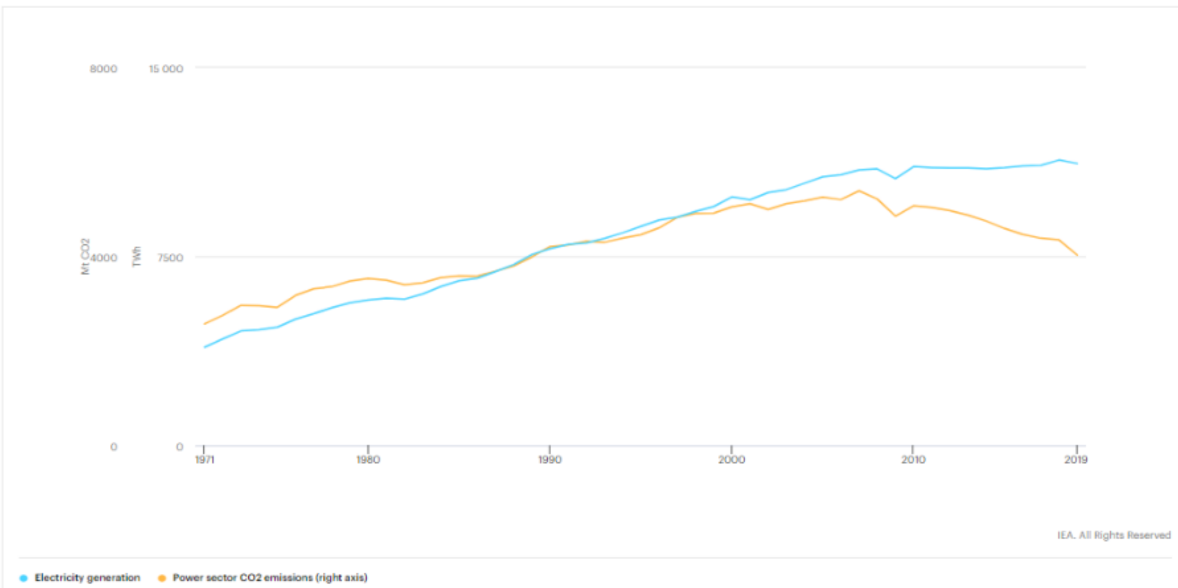
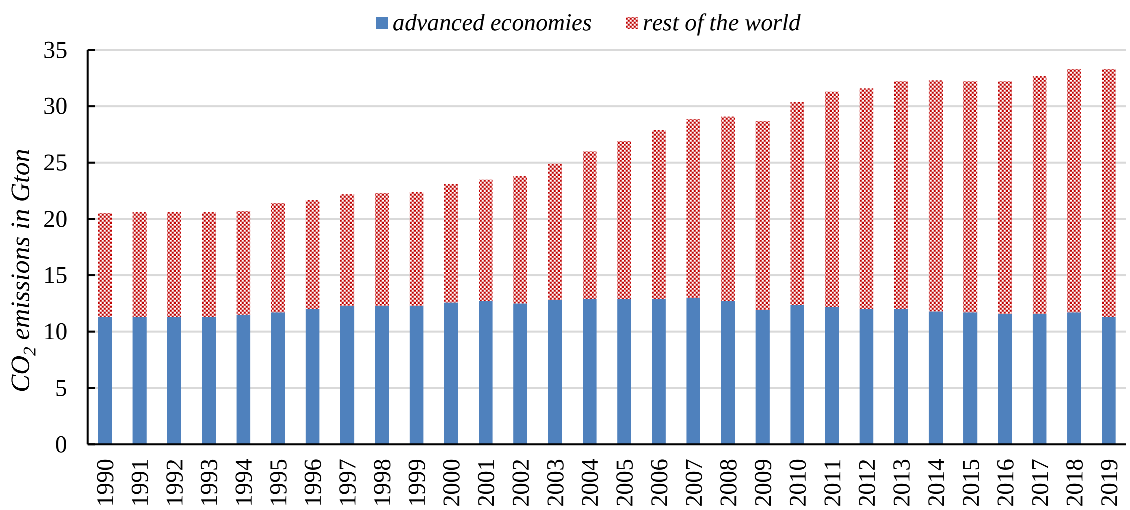


Figure 4.2: Electricity generation vs electricity power sector CO_2 emissions. Source: IEA [41]

We can appreciate how the advanced economies have reduced their overall emissions since 2007 to the levels in 2019, that have not been seen since 1980's. According to the *IEA*, the decrease is due to the electric power sector, responsible to "85%of the drop" [41], even when in the late 1980's, the total electricity demand was one third lower than it is at present. Such a notable decrease is main due to the declining use of coal plants, who are being replaced progressively by natural gas and oil plants, as well as renewable sources, which emit less CO_2 to the atmosphere. However, there is some very illustrative data. If we get the sum of all the population of what are considered advanced economies for the *IEA*, we get 1,335.93

million people (2017), approximately 17.5 % of the globe's population. That percentage is responsible for the 35.47 % of the total CO_2 emissions. If all the countries around the world kept the same rhythm of CO_2 emitting tendency, we would be getting 66.28 gigatons (*Gton*) CO_2 emissions each year. To state it clear, 1 *Gton* = 10^9 *tons*, and 1 *Mton* = 10^6 *tons*. Therein lies the reason for the importance to not only reduce the emissions by nations like China, responsible for the largest share of global emissions, but also to follow such a trend by the developed nations and regions, including Spain or California, and their electric power sectors continue to play critically important roles to attain future reductions..



Advanced economies include: Australia, Canada, Chile, EU, Iceland, Israel, Japan, Korea, Mexico, Norway, New Zealand, Switzerland, Turkey and US)

Figure 4.3: World CO_2 emissions (1990 – 2019). Advanced economies and rest of the world

4.1. Key environmental attributes of the two regions' electric sectors

CAISO provides data on the evolution of the monthly CO_2 emissions by the electricity sector. The lowest monthly CO_2 emissions occur during the April - May. During the July - August period each year, the CO_2 emissions become considerably more pronounced. However, the deepening penetrations of renewable resources integrated in the CAISO grid have each year reduced CO_2 emissions. The effects of this trend is illustrated in Figure 4.4, which shows the yearly decline during the 5-year period from January 2014 to December 2018. Overall CO_2 emissions have been reduced from 68.781 million tons of CO2 in 2014 to 52.857 million tons of CO_2 in 2017. The trend did not continue in 2018, which experienced a 2% increase in CO_2 emissions. Solar *PV* resources, together with large hydro resources, are instrumental in the CO_2 emission reductions. In 2015, only 5.88 % of the total *CAISO* generation came from hydro sources, while in 2016 the hydro share increased to 12.30 % and in 2017 grew even larger to 17.89 %.

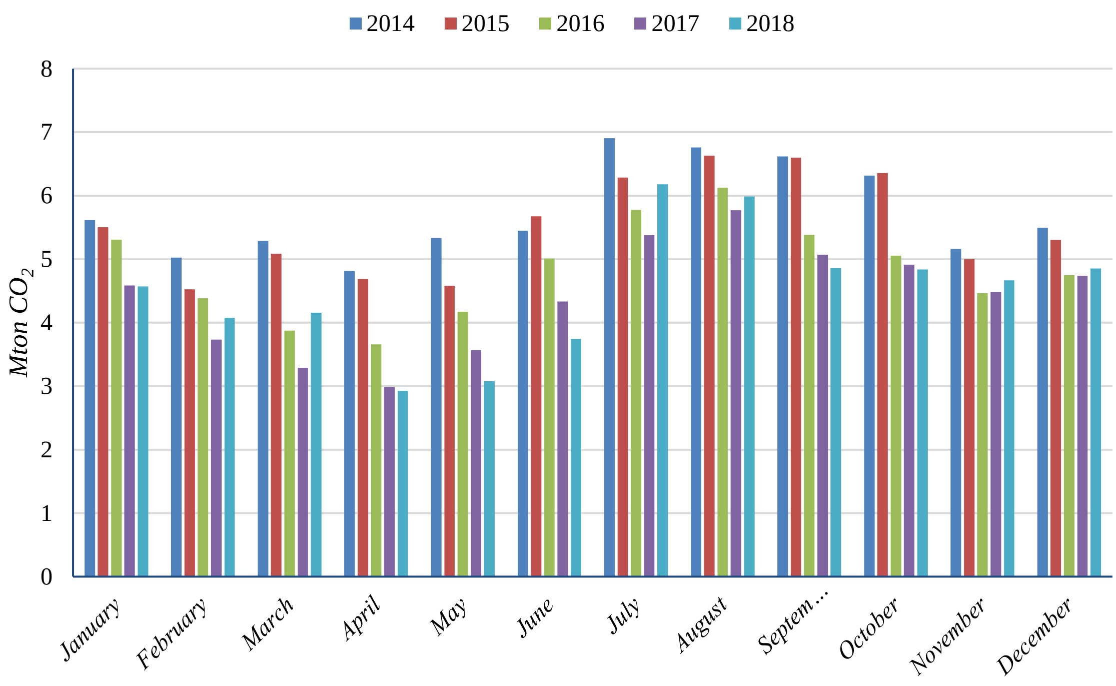


Figure 4.4: Monthly CO_2 emissions associated to the electricity power sector in California (2014-2018)

This tendency is reflected in Figure 4.5. Overall CO_2 emissions have been reducing progressively year by year, going from 68.781 million tons of CO_2 in 2014 to 52.857 million tons of CO_2 in 2017, value that increased a 2 % in 2018. Solar *PV* plays a big role in this CO_2 emission reduction, as well as large hydro. In 2015, only 5.88 % of the total California's generation came from hydro sources, while in 2016 that percentage was 12.30 % and in 2017 grew even more, up to 17.89 %.

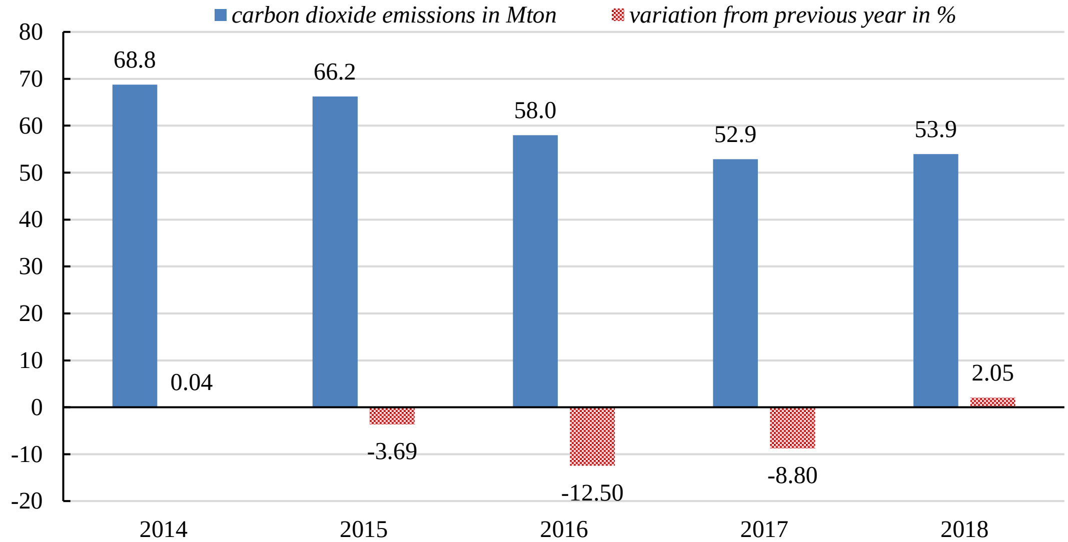


Figure 4.5: Overall CO_2 emissions associated to the electricity power sector in California

In Spain, the amount of total emissions associated to the electricity generation varies a lot year to year, depending significantly in the percentage of renewable energy generation, which is strongly related to the hydro generation. When a year is especially dry, the percentage of the hydro generation contribution to the grid gets lower, and the amount of CO_2 emissions gets bigger. In 2014, 2016 and 2018 the hydro generation was above 33,000 *GWh*. In 2015 it decreased to 28,000 *GWh*, and the coal plants generation grew 25 *%* compared to the previous year, which explains that 27.93 *%* increase in the CO_2 emissions. And in 2017, something similar. Hydro generation decreased 48.9 *%* compared to 2016, and the contribution to the generation of coal and combined cycle plants increased 20 *%* and 27.7 *%* respectively.

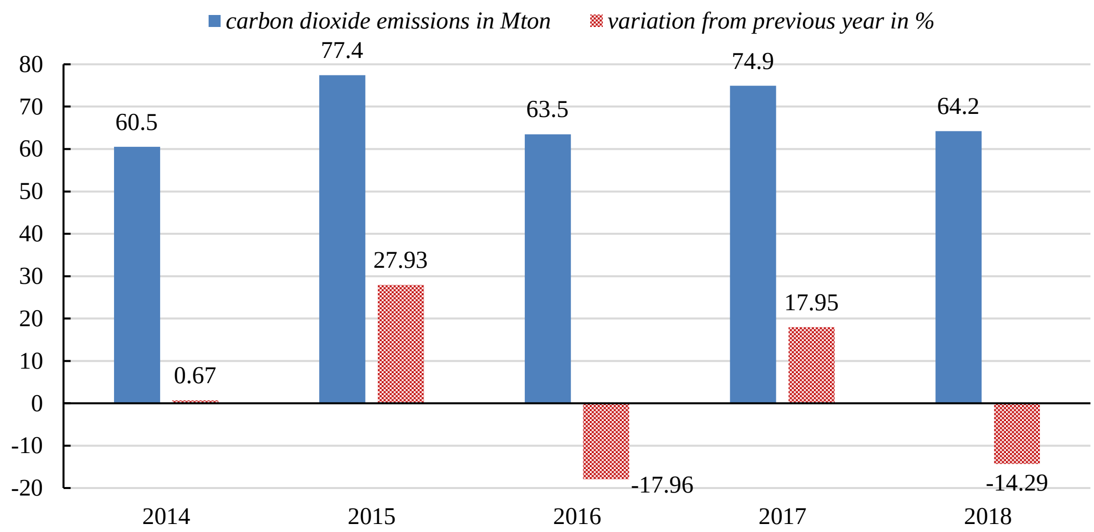


Figure 4.6: Overall CO_2 emissions associated to the electricity power sector in Spain

4.2. The role of solar resource generation in CO_2 emission reductions in California and Spain

In order to compute the number of CO_2 emissions prevented to go into the atmosphere, there is not a standard method of calculation, as one of the key factors to calculate those , the emission coefficients, the way they are obtained and what factors are taken into account vary depending on which agency provides the data. For example, it is well accepted that renewable sources do not produce emissions to the atmosphere. However, this assumption obvious the process of manufacturing and transportation, which produces CO_2 emissions.

The computation of the CO_2 emissions avoided by solar resources require some basic data for each region. The data include the electricity generation per year for each solar resource (*PV* and *CSP*), the electricity generation per year for technologies which use fossil fuels, the CO_2 emission coefficients associated to those fossil fuel technologies and the associated CO_2 emission coefficient associated to each grid, provided by *CAISO* in the case of California and *REE* in the case of Spain.

2 different methods have been used to compute the CO_2 emissions avoided in each region. The first method, which will be called "Complex Computation Method· (*CCM*), is more complex, while the second method is simpler, and will be called "Direct Computation Method" (*DCM*). Those 2 different methods will be used, as said before, to compute the CO_2 emissions avoided by each different solar resource in California and Spain, but although both methods are expected to provide similar results, some differences will be present, as *CCM* includes the CO_2 emissions associated to solar *PV* and *CSP*. Those are emissions, though being minor compared to fossil fuel technologies, exist and should be taken into account, that is why *CCM* should be a more realistic approach compared to *DCM*, which only uses the CO_2 emission coefficient associated to the grid, provided by the California Energy Commission and *REE*.

Table 4.1: The 2014 – 2016 CO_2 emissions for solar *PV* generation, and their equivalent for coal, natural gas and oil in the *US* [35]

	year		
	2014	2015	2016
solar *PV* electricity generation in *GWh*	21,915	32,091	46,633
emissions associated in *Mton* CO_2	1.01	1.47	2.15
equivalent emissions for coal in *Mton* CO_2	21.94	32.12	46.68
equivalent emissions for natural gas in *Mton* CO_2	10.28	15.05	21.87
equivalent emissions for oil *Mton* CO_2	18.41	26.96	39.17

Starting with *CCM*, we need the emission coefficients associated to the generation of each type of technology. In the case of California, these coefficients have been extracted trough *IRENA*. *IRENA* Avoided Emission Calculator [35] provides data on total emissions avoided, even for renewable sources. Using the data of the generation of the solar resource, the associated CO_2 emissions to that generation and the equivalent CO_2 emissions for other non-renewable technologies, we can extract the CO_2 emission coefficients associated with the different types of technology. In Table 4.1, we give an example. We can see in Table 4.1 the data of Solar *PV* in the United States for the years 2014-2016. It provides the total electricity generation of Solar *PV* resources, the emissions of CO_2 associated to that generation and the equivalent of emissions for different types of technology, in this case coal, natural gas and oil.

With the data provided by Table 4.1, we can conclude that the coefficients do not vary from year to year, and we will be using those coefficients for *CCM* in California, which are the following that appear in Table 4.2.

Table 4.2: CO_2 emission coefficients associated to California

technology	Coefficient in *kgCO₂/kWh*
solar *PV*	0.046
CSP	0.022
coal	1.001
natural gas	0.469
oil	0.840

As we have seen in Chapter 2, Spain's grid is much more diverse so there are more technologies that emit considerable CO_2 emissions. The coefficients used for Spain are the following that appear in Table 4.3. For solar technologies, the coefficient used has been provided by *IRENA* [35], while the rest have been obtained by [47].

Table 4.3: CO_2 emission coefficients associated to Spain

technology	coefficient in $kgCO_2/kWh$
solar *PV*	0.046
CSP	0.022
coal	0.999
cogeneration	0.370
combined cycle	0.460
fuel+gas	0.745
non-renewable waste	0.200

To calculate the emissions avoided, we need first the generation by each type of technology from 2008 to 2018, which are included in Table 4.4 for California and table 4.5 for Spain

Table 4.4: Fossil fuel technologies electricity generation in *GWh* in California

	technology		
year	coal	natural gas	oil
2008	2,835	122,799	92
2009	2,562	117,099	67
2010	2,286	109,682	52
2011	2,096	91,063	36
2012	1,262	121,776	49
2013	824	120,863	39
2014	802	121,855	45
2015	309	117,565	54
2016	324	98,879	37
2017	302	89,596	33
2018	294	90,642	35

Table 4.5: Fossil fuel technologies electricity generation in *GWh* in Spain

	technology				
year	coal	combined cycle	cogeneration	fuel+gas	non-renewable waste
2008	46,508.4	93,197.5	9,887.6	9,887.6	2,485.6
2009	34,793	80,223.8	9,276.3	9,276.3	2,623
2010	23,700.6	66,799	8,821.7	8,821.7	2,970.8
2011	43,177.5	53,430.9	7,007.9	7,007.9	1,287.8
2012	53,779.9	41,074.4	7,094.6	7,094.6	1,589.4
2013	39,441.5	27,569.9	6,563.8	6,563.8	1,617.2
2014	41,951.8	24,828.8	5,776	5,776	1,965.9
2015	52,616.5	29,027.3	6,483.8	6,483.8	2,480.1
2016	37,313.8	29,006.5	6,754.6	6,754.6	2,607
2017	45,019.4	37,065.8	7,001.6	7,001.6	2,608
2018	37,276.8	30,044.5	6,682.9	6,682.9	2,435

In Tables 4.6 and 4.7, we have the total net generation by solar resource in both regions.

Table 4.6: Solar resource generation in *GWh* in California

	technology	
year	solar *PV*	*CSP*
2008	3	730
2009	17	841
2010	90	879
2011	226	889
2012	1,018	867
2013	3,772	686
2014	9,148	1,624
2015	13,057	2,446
2016	17,385	2,548
2017	21,895	2,464
2018	24,488	2,545

Table 4.7: Solar resource generation in *GWh* in Spain

	technology	
year	solar *PV*	*CSP*
2008	2498	15.4
2009	6072.4	129.8
2010	6422.8	691.6
2011	7440.8	1861.6
2012	8202.3	3447.5
2013	8327.3	4441.5
2014	8207.9	4958.9
2015	8243.6	5085.2
2016	7977.5	5071.2
2017	8397.8	5348
2018	7766.2	4424.3

With the electricity generation data of Tables 4.4 and 4.5 for each region, we can then extract what we call a "hypothetical reference case". This hypothetical reference case simulates how the generation from solar PV or CSP from every year would have been distributed if it were generated by other non-renewable resources, with their different shares. Tables 4.8 and 4.9 show the "hypothetical reference case" for California and Spain, respectively.

Table 4.8: Hypothetical reference case for California

	share of different technologies in %		
year	coal	natural gas	oil
2008	2.25	97.67	0.07
2009	2.14	97.80	0.06
2010	2.04	97.91	0.05
2011	2.25	97.71	0.04
2012	1.03	98.93	0.04
2013	0.68	99.29	0.03
2014	0.65	99.31	0.04
2015	0.26	99.69	0.05
2016	0.33	99.64	0.04
2017	0.34	99.63	0.04
2018	0.32	99.64	0.04

Table 4.9: Hypothetical reference case for Spain

	share of different technologies in %				
year	coal	cogeneration	combined cycle	fuel+gas	non-renewable waste
2008	26.38	13.74	52.86	5.61	1.41
2009	22.75	17.00	52.46	6.07	1.72
2010	18.17	21.56	51.23	6.76	2.28
2011	31.87	22.58	39.43	5.17	0.95
2012	39.55	23.86	30.21	5.22	1.17
2013	37.20	29.08	26.00	6.19	1.53
2014	42.51	24.48	25.16	5.85	1.99
2015	45.43	21.76	25.06	5.60	2.14
2016	36.73	25.50	28.55	6.65	2.57
2017	37.55	23.53	30.91	5.84	2.18
2018	35.35	27.51	28.49	6.34	2.31

In order to calculate the emissions generated by the hypothetical reference case, we will use equation 4.1, but first we need to define:

- M = annual CO_2 emissions in *Mton* associated to the hypothetical reference case
- S = Solar resource generation each year in *GWh*, tech=*PV* or *CSP*
- $A_{tech,year}$ = Percentage of the reasonable energy mix associated to a technology an specific year. Ex. $A_{Coal,2008}$=26.36 (Table 4.8)
- α_{tech} = CO_2 emission coefficient associated to each type of technology in *$kgCO_2$/kWh*

$$M = S * \left(\Sigma A_{tech,year} * \alpha_{tech}\right) * 10^{-3}\ (Mton) \tag{4.1}$$

To compute the CO_2 emissions associated to the generation of solar resources, we use equation 4.2, but first we need to define:

- E = annual CO_2 emissions in *Mton* associated to the solar resource

- S = solar resource generation each year in *GWh*
- β_{tech} = CO_2 emission coefficient associated either to *PV* or *CSP* in *kgCO₂/kWh*

$$E = S * (\beta_{tech}) * 10^{-3} \ (Mton) \tag{4.2}$$

Combining equations 4.1 and 4.2, we can obtain the avoided CO_2 emissions associated to each solar resource in each region using *CCM*.

Being C the avoided CO_2 emissions by each solar resource using *CCM*:

$$C = M - E \ \ (Mton) \tag{4.3}$$

Tables 4.10 to 4.13 gather all the results for the avoided CO_2 emissions by each solar resource in each region.

Table 4.10: *CCM*-calculated avoided CO_2 emissions in *Mton* due to California *PV* generation

	year										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
E	0.0001	0.0008	0.0041	0.0104	0.0468	0.1735	0.4208	0.6006	0.7997	1.0072	1.1264
M	0.0014	0.0082	0.0432	0.1087	0.4831	1.7831	4.3235	6.1442	8.1862	10.3109	11.5305
C	0.0013	0.0074	0.0391	0.0983	0.4363	1.6096	3.9027	5.5435	7.3865	9.3037	10.4040

Table 4.11: *CCM*-calculated avoided CO_2 emissions in *Mton* due to California *CSP* generation

	year										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
E	0.0161	0.0185	0.0193	0.0196	0.0191	0.0151	0.0357	0.0538	0.0561	0.0542	0.0560
M	0.3513	0.4042	0.4219	0.4277	0.4115	0.3243	0.7675	1.1510	1.1998	1.1604	1.1983
C	0.3353	0.3857	0.4026	0.4081	0.3924	0.3092	0.7318	1.0972	1.1437	1.1061	1.1424

Table 4.12: *CCM*-calculated avoided CO_2 emissions in *Mton* due to Spain *PV* generation

	year										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
E	0.1149	0.2793	0.2954	0.3423	0.3773	0.3831	0.3776	0.3792	0.3670	0.3863	0.3572
M	1.3679	3.2128	3.2531	4.4208	5.3051	5.3401	5.4896	5.6350	5.0587	5.3262	4.8659
C	1.2530	2.9335	2.9577	4.0785	4.9278	4.9571	5.1120	5.2558	4.6917	4.9399	4.5087

Table 4.13: *CCM*-calculated avoided CO_2 emissions in *Mton* due to Spain *CSP* generation

	year										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
E	0.0003	0.0029	0.0152	0.0410	0.0758	0.0977	0.1091	0.1119	0.1116	0.1177	0.0973
M	0.0084	0.0687	0.3503	1.1060	2.2298	2.8482	3.3166	3.4760	3.2157	3.3919	2.7720
C	0.0081	0.0658	0.3351	1.0651	2.1539	2.7505	3.2075	3.3642	3.1042	3.2743	2.6747

For the second method used, *DCM*, we need the CO_2 coefficient associated to the electricity generation of the regions of California and Spain. These coefficients are shown next in Table 4.13. As mentioned before, these coefficients are extracted from the California Energy Commission [40] website in the case of California, while in the case of Spain, these are extracted from the *REE* annual reports [8-17]

Table 4.14: CO_2 emission coefficients in *kgCO₂/kWh* associated to electricity production

region	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
California	0.685	0.427	0.427	0.427	0.427	0.427	0.427	0.427	0.427	0.427	0.427
Spain	0.602	0.580	0.552	0.624	0.664	0.648	0.679	0.696	0.647	0.652	0.638

Having those coefficients and using again the data from Tables 4.6 and 4.7, which contain the solar resource generation from California and Spain, we can directly compute the avoided CO_2 emissions, using equation 4.4. We define:

- C* = Avoided CO_2 emissions by solar resource using *DCM*. (*Mton*),
- S = Solar resource generation each year (*GWh*), tech=*PV* or *CSP*
- µ = CO_2 emission coefficient associated to each year in each region. (*kgCO₂/kWh*)

$$C^* = S * \mu * 10^{-3} \ \ (Mton\ CO_2) \tag{4.4}$$

Tables 4.15 to 4.18 gather all the results for each solar resource in each region.

Table 4.15: *DCM*-calculated avoided CO_2 emissions in *Mton* due to California *PV* generation

	year										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
C*	0.0021	0.0073	0.0384	0.0965	0.4347	1.6106	3.9062	5.5753	7.4234	9.3492	10.4564

Table 4.16: *DCM*-calculated avoided CO_2 emissions in *Mton* due to California *CSP* generation

	year										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
C*	0.5001	0.3591	0.3753	0.3796	0.3702	0.2929	0.6934	1.0444	1.0880	1.0521	1.0867

Table 4.17: *DCM*-calculated avoided CO_2 emissions in *Mton* due to Spain *PV* generation

	year										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
C*	1.5041	3.5230	3.5449	4.6409	5.4424	5.3961	5.5701	5.7350	5.1638	5.4769	4.9536

Table 4.18: *DCM*-calculated avoided CO_2 emissions in *Mton* due to Spain *CSP* generation

	year										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
C*	0.0093	0.0753	0.3817	1.1611	2.2875	2.8781	3.3652	3.5377	3.2826	3.4879	2.8220

Summing up all the results obtained, the following graphs, Figures 4.7 and 4.8, summarize the emissions avoided per technology and method used and as it can be appreciated and was mentioned at the beginning of the chapter, in both regions, the two methods used provide similar results.

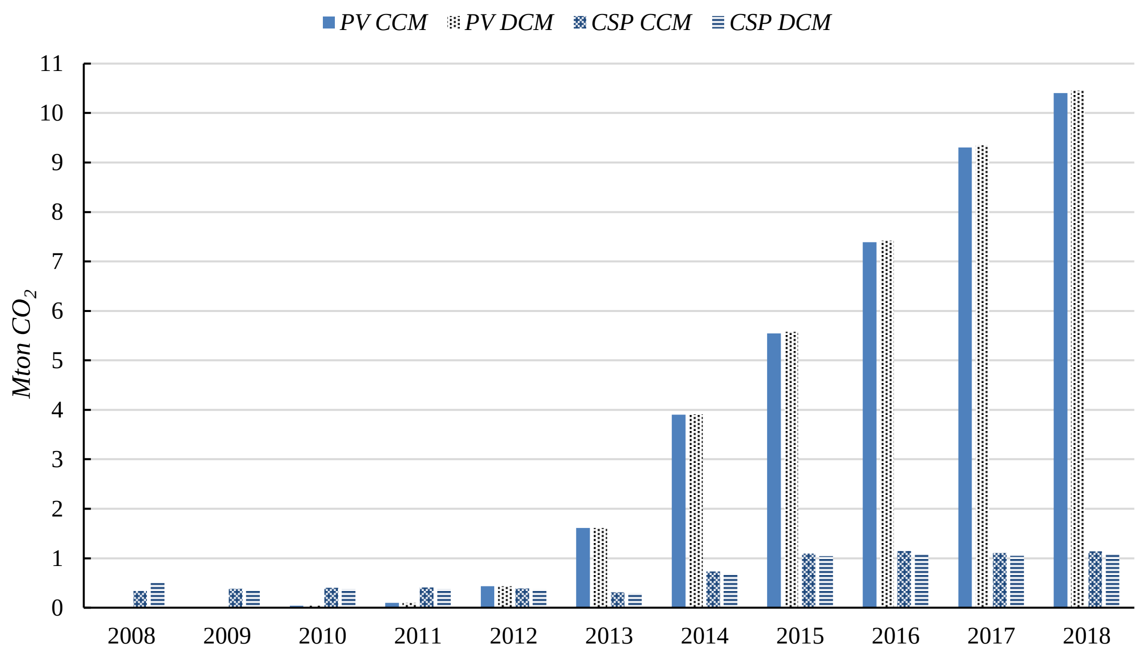


Figure 4.7: CO_2 emissions avoided in California by solar resource

As expected, the CO_2 emission reduction in California has increased considerably, as the solar generation increases year by year. *PV* has evolved from almost no CO_2 emissions avoided in 2008 to more than 10 million tons of CO_2 emitted per year, That is 10 times more than the emissions avoided by *CSP* technology. *CSP* avoids since 2015 near 1 million ton of CO_2 emissions per year,

In Spain, however, the emission reduction has decreased in the last few years, The *MW* installed are the same, and the generation is similar year to year, This decrease in the emissions avoided is due to the fact that Spain's grid is becoming 'greener', In solar *PV*, 2017 was the year with most energy generation, but the CO_2 emissions avoided are less than in 2014 or 2015, The reduction of the use of coal plants plays a role here, Coal is the technology which produces more CO_2 emissions, and the use of this type of plants, as we have seen, it is being reduced in Europe and North America, in benefit of other technologies, which can be renewables or fossil-fuel but with a less environmental impact, like combined cycle or natural gas plants.

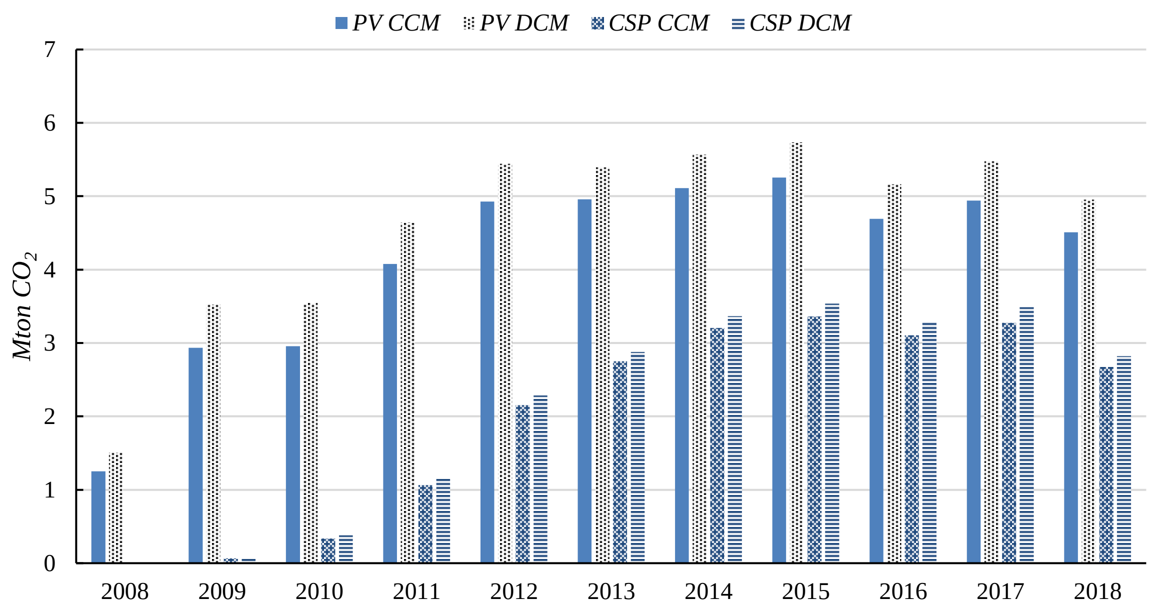


Figure 4.8: CO_2 emissions avoided in Spain by solar resource

When assessing both methods used in this computation of the CO_2 emissions avoided, it seems interesting how in the case of California, the emission reduction is higher in the case of *CCM* compared to *DCM* when comparing *PV*, but the emission reduction is higher using *DCM* compared to *CCM* when comparing *CSP*. However, as it can be appreciated in Figure 4.7, the difference is minimal. In the case of Spain, the emission reduction is higher when using DCM over CCM, and the difference is noticeable, as we can see above in Figure 4.8.

4.3. Environmental Challenges and Opportunities in the two regions

As mentioned at the beginning of Chapter 4, the Paris Agreement and the Kyoto Protocol are the two most known and significant agreements where measures have been proposed against climate change, global warming and the reduction of CO_2 particles emitted to the atmosphere. The Paris Agreement, which took place in Paris between the 30th November and 13th December of 2015, clearly express the concern on that matter, and as it mentions in paragraph 17 of the report published in January 2016 [45], in 2030 with the current estimations about greenhouse gas emission levels, there are projected 55 *Gton* of CO_2 emissions worldwide per year, when we are currently at less than 35 *Gton*. In that same paragraph, it is stated that much more efforts would be needed to hold the increase of the global average temperature below the desired 2 ºC above pre-industrial levels and having global CO_2 emissions not to exceed 40 *Gton* per year. To do so, as stated in paragraph 66 of that same report, the Technology Executive Committee and the Climate Technology Centre and Network will undertake further work related to future technology research and development, which will need to be demonstrated. However, the Paris Agreement makes a differentiation throughout all the document between developed and developing parties (countries) that have signed the agreement. As stated in paragraph 4, article 4 of the annex “developed country Parties should continue taking the lead by undertaking economy-wide absolute emission reduction targets. Developing country Parties should continue enhancing their mitigation efforts and are encouraged to move over time towards economy-wide emission reduction or limitation targets in the light of different national circumstances”. This brings up a dilemma on how much room developing countries are giving in order to accomplish their CO_2 emission goals compared to developed countries.

In the case of California and Spain, one way of continuing decreasing their overall CO_2 emissions is to continue to decarbonize their electric generation system, by replacing fossil fuel technologies with renewable energy sources. In Tables 4.19 and 4.20, we can see the amount of CO_2 emissions per *GWh* generated.

Table 4.19: Tons of CO_2 emitted per *GWh* generated in California

	year				
	2014	2015	2016	2017	2018
annual total generation in *GWh*	199,502	196,910	198,465	206,387	194,727
CO_2 annual emissions in *Mton*	66.8	66.2	58	52.9	53.9
tons CO_2 per *GWh*	334.83	336.19	292.24	256.31	276.80

Table 4.20: Tons of CO_2 emitted per *GWh* generated in Spain

	year				
	2014	2015	2016	2017	2018
annual total generation in *GWh*	254359.7	267453.9	261835.8	262305.9	260982
CO_2 annual emissions in *Mton*	60.5	77.4	63.5	74.9	64.2
tons CO_2 per *GWh*	237.85	289.40	242.52	285.54	245.99

We can observe how California has been reducing considerably the amount of CO_2 emissions per *GWh*, as we have seen due to the exponential growth of solar *PV* in the region, as seen in Chapter 2. However, in Spain, despite having a higher integration of renewable resources into the grid, for example in 2017, the tons of CO_2 emitted per *GWh* was higher compared to California. And this is the main problem of renewable resources. When there is an especially dry year, the contribution of hydro plants decays significantly. You can have a perfect solar day for solar *PV* and *CSP* plants, combined with the perfect wind speed for windfarms, but all those energy maybe not be used entirely because the region has already fulfilled the demand at that point in time, so that potential green generation is lost. Renewable energy sources are not dispatchable, so until there are not big improvements in energy storage, a higher integration of renewable sources will be complicated, and therefore, the level of decarbonization of the electricity of any region, in this case California or Spain, will not be significant compared to the actual scenario. Technologies like *CSP*, with their option to have thermal storage, and therefore having dispatchable energy, could play a role in this scenario, but as it will be seen in Chapter 5 the costs associated to this technology compared to Solar *PV*, makes it a less attractive option.

4.4. Conclusion

After the analysis, we can extract the following conclusions. Although developed countries are reducing their overall CO_2 emissions, as developing countries continue to grow at a steady rate, global CO_2 emissions will continue to increase. The Paris Agreement is trying to limit this growth at 40 *Gton* of CO_2 emissions per year, in order to achieve their goal of increasing the global temperature below 2 ºC compared to pre-industrial levels. Translated to the electricity generation sector, it plays a big role in reducing the CO_2 emissions, especially in developed countries. The introduction of more and more *MW* of solar energy into the grid is a good option in achieving this goal, helping reducing the CO_2 emissions, especially if this *MW's* of solar energy are introduced in order to replace fossil-fuel energy sources, especially the most pollutant, which are coal plants. However, this process is not immediate, as renewable energy sources are, in general, not dispatchable, so there is still and will be a need in having dispatchable energy sources, so electricity demand is satisfied at any point in time. The goal is transforming this dispatchable fossil-fuel sources into dispatchable renewable sources, so higher amounts of CO_2 emissions are avoided to go into the atmosphere, but future research and development is still needed to achieve this.

5. ECONOMIC ANALYSIS

One of the key aspects for the implementation of any technology is the cost associated to it. Renewable energy sources are getting more and more competitive and now, even without financial assistance, technologies like solar *PV* or wind have fallen into the fossil-fuel cost range. In the end, the electric power sector works like any other business, its final objective is to get the higher profit possible. Normally reducing the cost of the electricity generation translates into more profit. And it is important to know which technology is more competitive in a precise moment or could be more competitive in the future. But measuring different technologies, with different investment costs, different maintenance costs, etc. can be challenging. That is why, there are some coefficients that allow that comparison, like the levelized cost of energy.

The levelized cost of energy is a measure of a power source that allows the comparison of different methods of electricity generation. The levelized cost of energy of any power plant can be obtained with the next formula:

$$LCOE = \frac{II + \Sigma_{t=1}^{n} \frac{O\&M_t}{(1+i)^t}}{\Sigma_{t=1}^{n} \frac{G_t}{(1+i)^t}} \left(\frac{\$}{MWh}\right) \tag{5.1}$$

Where:

- II = Initial Investment ($)
- $O\&M_t$ = Cost of Operation and Maintenance at year t ($)
- I = Interest rate. For *OECD* countries an interest rate of 7.5 *%* is normally used.
- G_t = Electricity generation at year t (*MWh*)
- n = Life expectancy of the power plant. Normally the life expectancy of a solar *PV* or *CSP* plants is 25, 30 or 40 years.

5.1. *PV* Solar economic comparison: investment, operations and *LCOE* measures

Solar *PV* cost have been dramatically reduced in the last decade, making it one of the most attractive renewable technologies. In figure 5.1 we can take a look to how the *LCOE* of solar *PV* has decreased from 2010 to 2018 around the world. It has experienced a 77% drop during that period of time. This is thanks mainly to the big reduction of production costs of modules of all photovoltaic technologies: monocrystalline silicon, polycrystalline silicon or thin film.

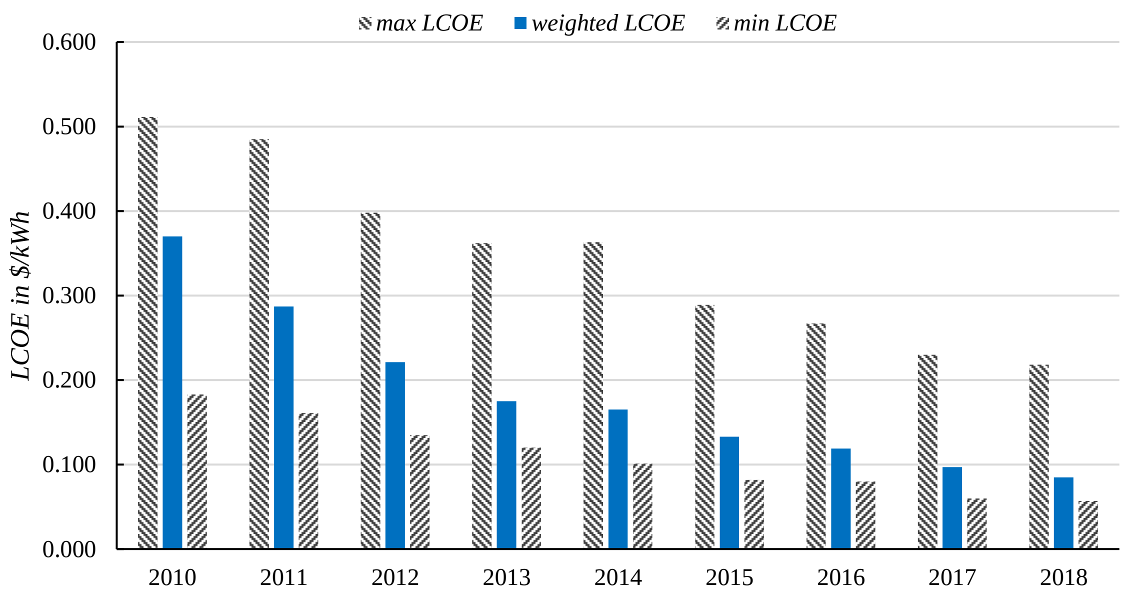


Figure 5.1: LCOE for solar *PV*. Source: *IRENA* [46]

This tendency can also be seen in the reduction installed cost of solar *PV* have experienced since 2010, where the weighted average was 4,620 *$/kW*, value that has become 1,210.2 *$/kW* in 2018.

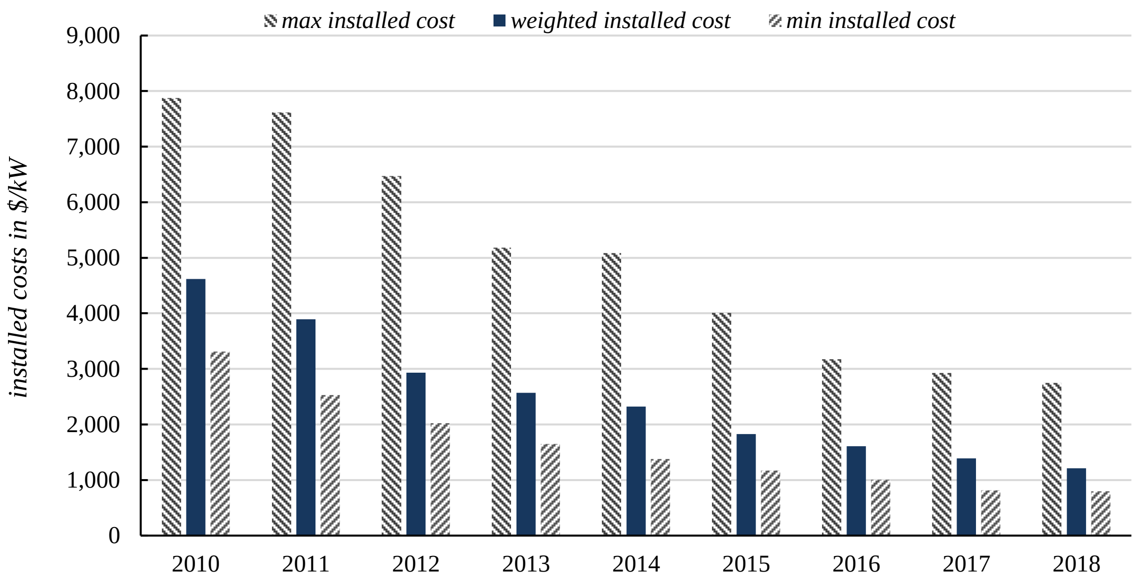


Figure 5.2: Installed cost for solar *PV*. Source: *IRENA* [46]

5.2. *CSP* Solar economic comparison: investment, operations and *LCOE* measures

CSP has not experienced the same drop in *LCOE* solar *PV* experienced in the same period of time. If we observe figure 5.3, there is not a clear tendency in the *LCOE* of *CSP*, due to the fact that the overall installed capacity around the world is really low compared to other renewable technologies. From 2011 to 2014 the *LCOE* decreased, which coincides with the creation of several projects in Spain, and the creation of the three big projects in California in 2014. In Appendix C there are two tables including all the currently *CSP* projects in California and Spain. The reduction in the *LCOE* in 2017 and 2018 is because China has commissioned a few projects. This will hopefully help with a future reduction in the costs, especially because the projects commissioned are projects with considerable thermal storage, up to 8 hours or more.

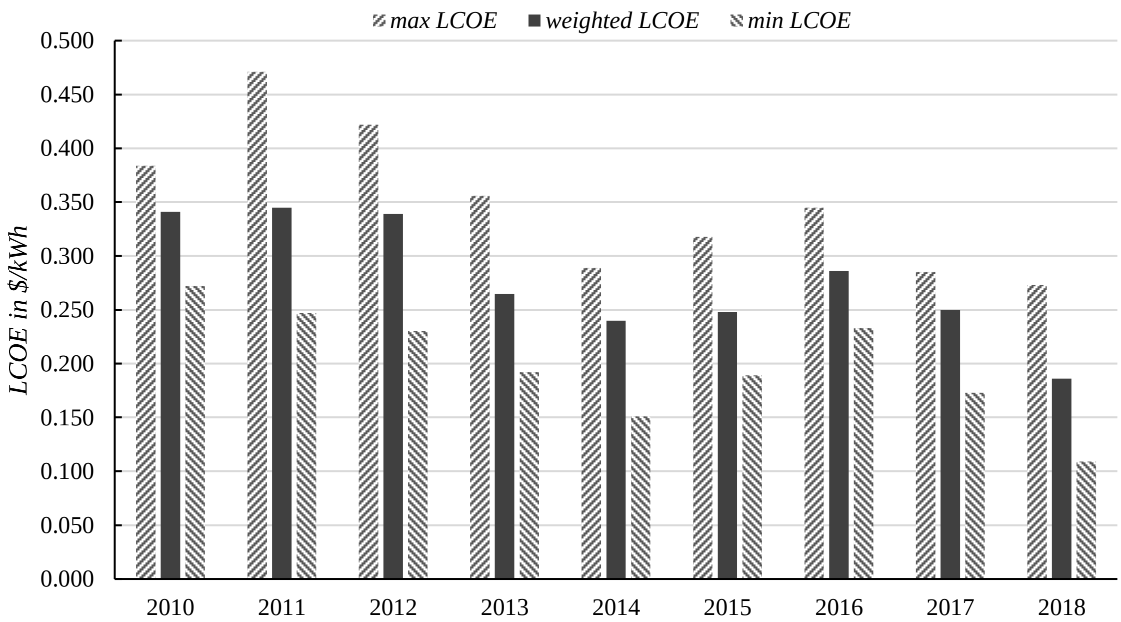


Figure 5.3: *LCOE* for *CSP*. Source: *IRENA* [46]

In 2014, there were built the 3 big *CSP* projects in California, The Ivanpah Solar Electric Generating System (solar power tower), the Genesis Solar Energy Project (parabolic trough) and the Mojave Solar Project (parabolic trough). As mentioned before, those 3 projects were not prepared for thermal storage. The *LCOE* for those plants was nearly 0.25 *$/kWh* in the case of Ivanpah Solar Electric Generating System and 0.24 *$/kWh* and 0.31 *$/kWh* in the case of the two parabolic trough projects. Between the years 2010 and 2012, when most of the *CSP* projects in Spain were built, the *LCOE* was considerably higher, varying from 0.28 to 0.39 *$/kWh* in 2010, 0.26 to 0.47 *$/kWh* in 2011, and from 0.29 to 0.46 *$/kWh* in 2012, although some projects include thermal storage, normally up to 7.5-8 hours.

This up and down tendency in the period that covers the years 2010 to 2018, can also be appreciate it in figure 5.4, that shows the installed costs for *CSP*.

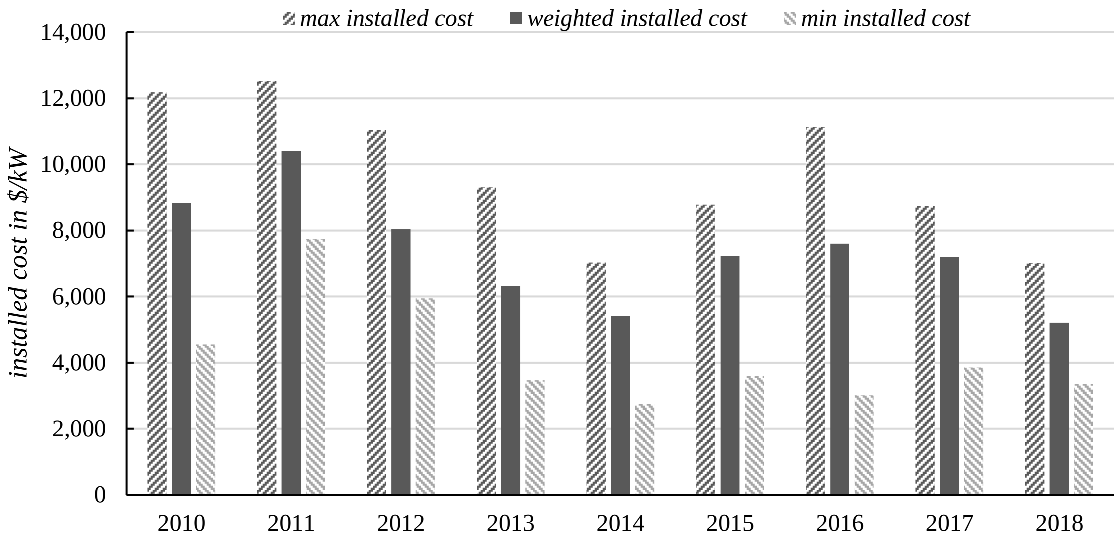


Figure 5.4: Installed cost for *CSP*. Source: *IRENA* [46]

5.3. *LCOE* Calculation

To better illustrate this evolution, we have calculated the *LCOE* for a hypothetical 50 *MW PV* plant, built in Spain or California, in two different years (2010 and 2018).

In table 5.1, we can find the different costs in $/W$_{DC}$ for a 50 *MW PV* plant, according to the NREL U.S Solar Photovoltaic System Cost Benchmark [49]. We have assumed this to be the cost of solar *PV* for both Spain and California.

Table 5.1: Breakdown of a 50 *MW PV* plant costs in 2010 and 2018 in *$/W$_{DC}$*

50 *MW PV* plant cost in 2010		
	fixed tilt	1-axis
module	2.12	2.12
inverter	0.24	0.24
structural BOS	0.2	0.38
electrical BOS	0.18	0.28
install labor and equipment	0.42	0.54
EPC overhead	0.25	0.3

50 *MW PV* plant cost in 2018		
	fixed tilt	1-axis
module	0.47	0.47
inverter	0.04	0.05
structural BOS	0.1	0.15
electrical BOS	0.1	0.1
install labor and equipment	0.1	0.11
EPC overhead	0.07	0.08

To calculate the approximate cost of the land for Spain and California, we have used current places where there are solar *PV* plants, like Adelanto in California and Puertollano in Spain. For Adelanto, the cost of the land is 0.7 $\$/m^2$, while for Puertollano, that value increases to 1.1 $\$/m^2$.

To calculate the total necessary area of a 50 *MW PV* plant, we have estimated a total of 1,000,000 m^2 for a fixed tilt plant. For a *PV* plant with 1-axis trackers, the needed area must be bigger, due to the necessity to space the arrays to avoid shading. For a 1-axis *PV* plant, we have estimated an increase of 20 *%* in the total area, being 1,200,000 m^2 the needed area.

Table 5.2: Expected costs of a 50 *MW PV* Plant in Spain and California in 2010 and 2018

	Spain				California			
	fixed tilt		1-axis		fixed tilt		1-axis	
	2010	2018	2010	2018	2010	2018	2010	2018
$\$/W_{DC}$	3.432	0.902	3.8864	0.9864	3.424	0.894	3.8768	0.9768
mill $	171.6	45.1	194.32	49.32	171.2	44.7	193.84	48.84

To calculate the expected generation, we have made the following assumptions:

- An average daily irradiation of 6.018 kWh/m^2*-day* in California and 4.916 kWh/m^2*-day* in Spain [51]
- An increase of 20% in the electricity production when using 1-axis trackers compared to fixed tilt. It is estimated that the increase in production varies between 15% and 30% when using 1-axis trackers. [49]
- A combined derate factor of 0.85. The combined derate factor measures the combined efficiency in transforming *DC* power to *AC* power due to different factors. These include inverter and transformer efficiency, mismatch, *DC* wiring, soiling, system availability, shading and module temperature. Each factor is assigned their own derate factor, which combined create the combined derate factor. This combined derate factor usually takes values between 0.75 and 0.85. [50]

To calculate the expected generation, we use equation 5.2.

$$Expected\ generation = P * \chi * \frac{H}{1\ kW\ /m^2} * 365 * \beta\ (MWh) \tag{5.2}$$

Where:

- P = Capacity of the plant in *MW*. In this case it is 50 *MW*.
- χ = Combined derate factor. As stated before, we use a value of 0.85 in this case.
- H = Average daily irradiation in *kWh/m^2-day*. We use 6.018 *kWh/m^2-day* in the case of California and 4.916 *kWh/m^2-day* in the case of Spain
- β = Performance coefficient. We use 1 in the case of fixed tilt and 1.2 in the case of 1-axis trackers.

Therefore, we can calculate the expected generation for that hypothetical 50 *MW PV* plant in Spain and California, when using fixed tilt arrays or 1-axis trackers. The results are shown in Table 5.3.

Table 5.3: Expected annual electricity generation of the 50 *MW PV* plant in *MWh*

	California	Spain
fixed tilt	93,354.23	76,259.45
1-axis	112,025.10	91,511.34

Once we have the expected annual generation, we need the Cost of Operation and Maintenance for the plant. We have used the stated *O&M* costs in the NREL U.S Solar Photovoltaic System Cost Benchmark [49] for utility scale solar *PV*. These are the following:

- In 2010, there were 28 *$/kW-yr* both for fixed tilt and 1-axis trackers
- In 2018 that value decreased to 14 *$/kW-yr* in the case of 1-axis trackers and *13 $/kW-yr* when using fixed tilt.

Therefore, for our hypothetical 50 *MW PV* plant, the *O&M* costs are the ones shown in Table 5.4.

Table 5.4: *O&M* costs for 50 *MW PV* plant in *$/yr*

	fixed tilt	1-axis
2010	1,400,000	1,400,000
2018	650,000	700,000

Finally, we calculate the *LCOE* for the hypothetical 50 *MW PV* plant, for the two locations, in two different years and with two different technologies. We have calculated the *LCOE* for four different interest rates: 2.5 *%*, 5 *%*, 7.5 *%* and 10 *%*. In addition, we have estimated a reduction of 0.5 *%* in the annual electricity generation every year, until reaching the lifespan of 25 years.

$$LCOE = \frac{II + \Sigma_{t=1}^{n} \frac{O\&M_t}{(1+i)^t}}{\Sigma_{t=1}^{n} \frac{G_t}{(1+i)^t}} \left(\frac{\$}{MWh}\right) \tag{5.1}$$

The calculated *LCOE* for every possible option is shown in Figures 5.5 and 5.6.

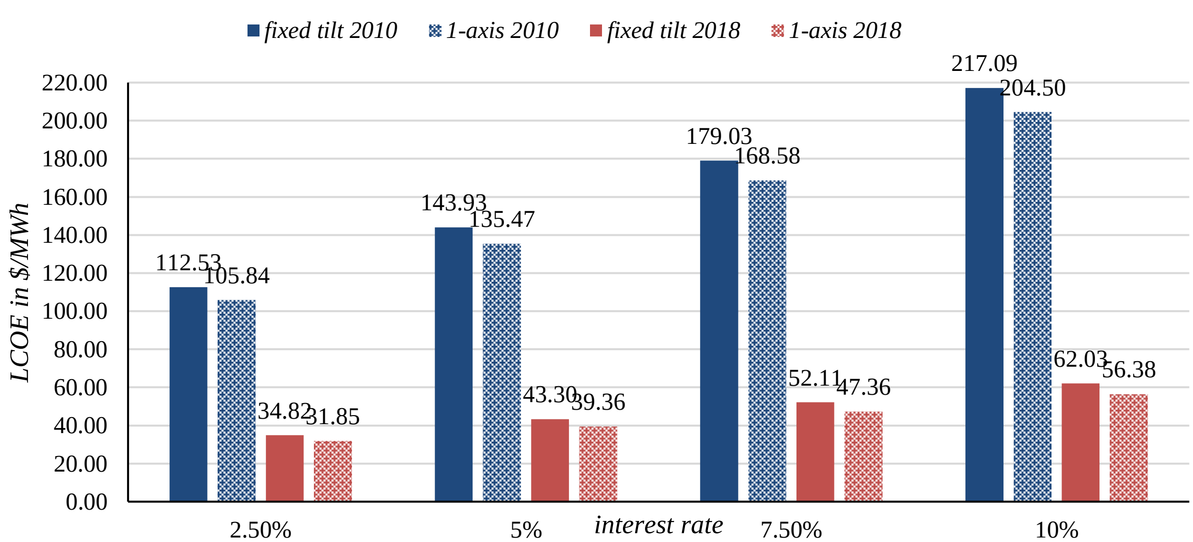


Figure 5.5: *LCOE* for 50 *MW PV* plant in California

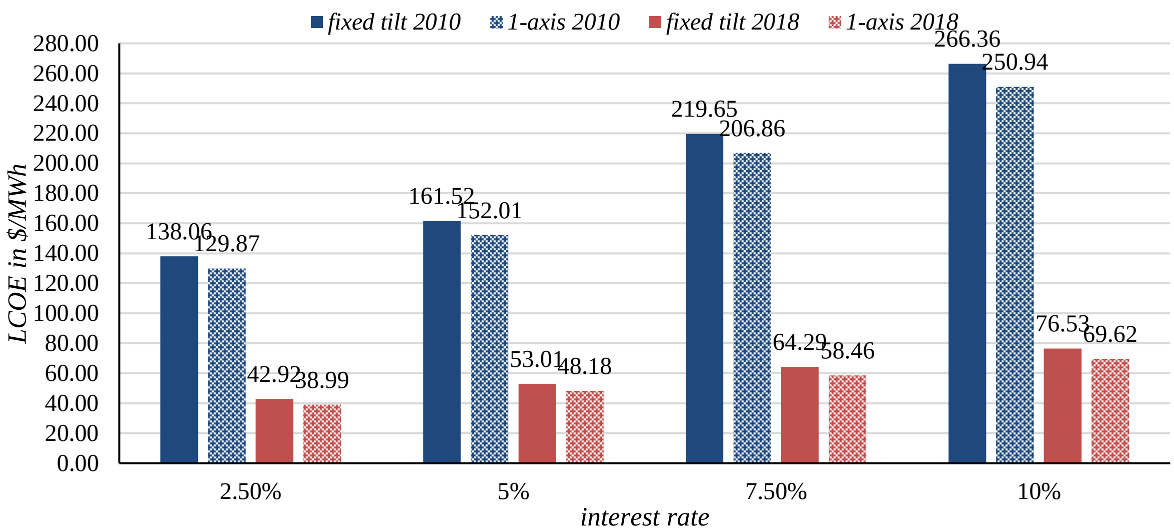


Figure 5.6: *LCOE* for 50 *MW PV* plant in Spain

As expected, the *LCOE* in California is lower than in Spain, due to the higher electricity generation that can be achieved thanks to a higher average daily irradiation. We can clearly see the big difference 8 years have made in terms of price competitiveness, with a massive reduction in the *LCOE* from 2010 to 2018, thanks to the progressive and steady reduction in the cost associated in building a *PV* plant. This tendency is expected to continue in the following years with costs being reduced more and more. In addition, we can see as well how the higher the interest rate, the higher the *LCOE* in every case. But, what is more interesting is how 1-axis trackers are a preferred option in every case compared to fixed tilts, despite needing much more land for the same installed capacity to avoid shading, higher initial investment and higher *O&M* costs. With a 20 *%* increase in production, 1-axis trackers are more competitive than fixed tilt arrays.

5.4. Role of Storage

Storage will be a key factor in the future development of renewable energy sources. It will allow to take advantage of greener energy in a wider spectrum. This will increase production, as for example a solar *PV* plants will be able to produce energy all the time there is sunlight, even if the demand is satisfied, as it this created energy would be stored and used at night time when is necessary. But there is a problem, the cost associated to this storage. There are research conducted in the development of battery storage, which will be interesting for solar

PV or wind energy for example. However, *CSP* has the capacity of adding thermal storage and have the advantage of becoming a dispatchable renewable energy source. However, it relies on the same problem as before, cost. As we have seen, *CSP* is not the most cheap energy among the renewable energy sources, and if there is the addition of thermal storage, the investment cost goes up quickly, as well as the operation and maintenance cost, as the tanks where the molten salts that sore the energy created, need a lot of maintenance to work properly. This thermal storage is normally a mix of sodium nitrate and potassium nitrate, which ais stored in tanks. It is significant that none of the *CSP* projects in California have the possibility of storing energy. In Spain on the other hand there are projects that make use of thermal storage, normally capable of storing between 7.5 and 8 hours of energy. However, out of the 50 *CSP* projects that are operative in 2018 in Spain, only 24 make use of the thermal storage. But this use, is not reflected on the performance, as the theoretical *c.f.*s of up to 40 % or even higher, are not achieved, as we have seen in chapter 2. So basically, is investing in something that will not achieve the level of efficiency and performance it was supposed to achieve in theory.

6. CONCLUDING REMARKS

In this chapter we summarize the work presented in this report and discuss some possible directions for future work.

6.1. Summary of the results presented

In this report, we have taken a look and compared the role solar energy sources play in the production of electricity in the regions of Spain and California. Firstly, before entering in the specific role of solar resources, we have taken a look at how the grids of Spain and California look and have evolved in the period that covers the years 2008 to 2018. We have seen that they follow similar trends when looking at the annual electricity consumption, that experiences similar variations year to year, being California's electricity consumption a bit higher. We have seen how the peak load from each year varies practically the same, reducing year by year, and both regions having achieved their historical maximum peak load in similar years, 2006 in the case of California and 2007 in the case of Spain. Although having similar energy consumption, we have seen how the approach to satisfy that consumption is completely different. Spain, depending on the year, export or imports electricity through the interconnections with its neighbor countries, France and Portugal, and its generation covers practically the demand the years imports are needed. On the other hand, California imports huge amounts of electricity from other states, like Oregon, Nevada or Arizona. These imports cover more than 30 % of the consumption from every year. Their grids are very different as well. While California, relays basically on 3 technologies to produce energy (natural gas plants, hydroelectric plants and solar *PV* plants), Spain's grid is much more diverse in terms of technologies, having windfarms and combined cycle plants special relevance. Also, we have analyzed the role of renewables in the region's annual electricity generation. Spain's has been steady above 30 % of renewable generation every year since 2010, while California has achieved that percentage in 2018 thanks to the quick and massive implementation of solar *PV* plants in the grid over the last few years, tendency that still continues for the following years.

We have also analyzed more in depth the solar resources and potential of both solar technologies (*PV* and *CSP*). California was the precursor of *CSP* technology with the SEGS plants in the 1980's, but it was not until 2014 when 3 more projects were connected to the grid. Spain, was also the precursor of this type of technology in Europe, being the first country to build a commercial solar power tower in 2008 with Andasol-1. There was a huge growth until 2013, when 50 projects built throughout the Spanish geography, making it the leader in terms of installed capacity around the world. With the irruption of China that will probably be changing in the near future. *CSP* presence in the grid it is not big in neither of both regions with, 2.12 % of the installed capacity and 2 % of the total net generation in 2018 in Spain. In California, very similar. 1.3 % of the installed capacity and 1.55% of the total electricity that was produced in 2018. Solar *PV* instead, has followed a different trend, especially in California, where is the 3rd technology in 2018 in terms of capacity installed and electricity generation. It has undoubtedly become the preferred solar technology, and it is thanks to the reduction principally in the manufacturing process of the modules, and we have briefly seen in chapter 5, it has even become a competitive technology when compared to fossil-fuel fired plants even without financial assistance. 13.27 % of all the installed capacity in California in 2018 comes from solar *PV* plants, which provided 12.57% of the total net generation of that year. In Spain, solar *PV* is gaining importance despite the tiny growth that has experienced since 2012. In 2018, the 4,714 *MW* of solar *PV* plants provided 3 % of the total electricity generation. We have taken a look also at the efficiency of both technologies, concluding that in general, the overall efficiency of *CSP* and *PV* is higher in California, which makes sense due to the higher solar irradiation.

We have computed the CO_2 emissions avoided by each solar technology. For this, we have used two different method of computation with different approaches. *CCM* method was more complex as it used more data and took the emissions associated to the manufacture of the components needed to build a solar *PV* or *CSP* plants, while *DCM* method was direct and used the electricity emission coefficients that California Energy Commission and *REE*, the operators of the grid in California and Spain respectively, publish in their reports and webpages. It was also interesting to develop the calculation of the *LCOE* for the hypothetical 50 *MW PV* plant and compare the evolution *PV* solar has experienced from 2010 to 2018 in terms of cost, as well as how the *LCOE* evolves with different interest rates and with different technologies used for the plant.

6.2. Directions for future work

It would be interesting, to see how solar *PV* and *CSP* will be developing in the next 10 years. As more research is done and at the rates solar *PV* for example are developing nowadays, the grid in 10 years may be completely different as today. In addition, the current investigation in battery storage could be very beneficial for renewable energy sources like solar *PV* or wind. Could be a complete game changer and help in the objective of decarbonizing the grids around the world and reduce the dependence we still have in fossil-fuel energy sources. *CSP*, could play a role also, as is an already mature technology that already supports thermal storage. With the introduction and investment of China in this technology, hopefully *CSP* starts follow the cost reduction tendency solar *PV* has been experienced and starts to be a great alternative.

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APPENDIX A – SDGs PRINCIPLES REFLECTION

The 17 Sustainable Development Goals (*SDG*s) are several objectives inside the 2030 Agenda for Sustainable Development created by the United Nations and adopted by all the *UN* Member States back in 2015. These *SDG*s, in words from the *UN*, "are an urgent call for action by all countries in a global partnership. They provide a shared blueprint for peace and prosperity for people and the planet, and recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth, all while tackling climate change and working to preserve our oceans and forests". *SDG*s cover a wide spectrum of different objectives, divided in three different dimensions: biosphere (*SDG*s 6, 13, 14 & 15), society (*SDG*s 1, 2, 3, 4, 5, 7, 11 & 16) and economy (*SDG*s 8, 9, 10 & 12). This project, as it is a comparison of the solar energy role in the supply of electricity, identifies clearly with *SDG*7: Affordable and clean energy. The main description of this *SDG* is the following: "ensure access to affordable, reliable, sustainable and modern energy for all". Solar energy fits perfectly this description now, as thanks to the progressive and steady development it has become and affordable energy source, it is reliable and modern, and even more important, it is a sustainable energy source, as the energy is extracted from the sun in all its variants, being one of the main standard bearers of renewable energy. And this seems like the beginning, with improvements in efficiency and reduction in costs that will make it even more affordable and a serious and valid option for energy production in the near future for more and more countries.

The *SDG*s have several targets that need to be achieved. As said previously, this project identifies clearly with *SDG*7, but furthermore, it interacts with targets 7.2 and 7.3. These targets have the following definitions respectively: "By 2030, increase the share of renewable energy in the global energy mix" and "By 2030, double the global rate of improvement in energy efficiency". Throughout this report, especially in Chapter 2, we have seen how the share of renewables in the energy production of California and Spain has increased, being these two regions amongst the ones that have a bigger share of renewable energy in their global energy mix. This increase is thanks to the investment in renewable energy sources like solar energy. In addition, in this report we have seen how the efficiency of solar energy resources has improved over the last few years, making it a more efficient energy source year by year. This is how this report interacts with the *SDG*7 and its targets.

Although *SDG*7 is the most obvious and primary sustainable development goal with which this report identifies, there are others like *SDG*13: Climate Action, who identify as well with the work that has been done in this project. Climate change is a big challenge we need to face to preserve the wellbeing and sustainable future of our planet. *SDG*7 and *SDG*13 are related, as the purpose of the introduction of renewable energy sources is to provide alternate energy sources which help to reduce the amount of greenhouse emissions that contribute to pollute the atmosphere. This fits the description of *SDG*13, “take urgent action to combat climate change and its impacts”. Clearly, *SDG*7 and *SDG*13 are related, and this project, having analyzed the amount of CO_2 emissions avoided by solar energy sources, interacts with the objectives of *SDG*13 of combating climate change with the introduction of greener energy sources.

APPENDIX B

Table B.1: Net electricity generation (*GWh*) in California per year (2008-2013)

	year					
technology	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
coal	2,835	2,562	2,286	2,096	1,262	824
petroleum coke	1,142	1,173	1,120	1,024	318	194
biomass	5,911	6,117	5,989	6,060	6,211	6,559
geothermal	12,907	12,907	12,740	12,685	12,733	12,510
nuclear	32,482	31,509	32,214	36,666	18,491	17,860
natural gas	122,799	117,099	109,682	91,063	121,776	120,863
large hydro	19,887	23,659	28,483	35,682	22,737	20,319
small hydro	4,573	4,880	5,707	7,055	4,724	3,782
solar *PV*	3	17	90	226	1,018	3,772
CSP	730	841	879	889	867	686
wind	5,724	6,249	6,172	7,598	9,242	11,964
waste heat	278	233	241	267	217	222
oil	92	67	52	36	49	39
total	209,363	207,313	205,655	201,347	199,645	199,594

Table B.2: Net electricity generation (*GWh*) in California per year (2004-2018)

	year				
technology	**2014**	**2015**	**2016**	**2017**	**2018**
coal	802	309	324	302	294
petroleum coke	208	229	207	246	207
biomass	6,785	6,367	5,905	5,847	5,909
geothermal	12,186	11,994	11,582	11,745	11,528
nuclear	17,027	18,525	18,931	17,925	18,268
natural gas	121,855	117,565	98,879	89,596	90,642
large hydro	13,739	11,569	24,410	36,920	22,096
small hydro	2,742	2,427	4,576	6,384	4,248
solar *PV*	9,148	13,057	17,385	21,895	24,488

CSP	1,624	2,446	2,548	2,464	2,545
wind	13,104	12,191	13,499	12,867	14,244
waste heat	237	177	182	163	223
oil	45	54	37	33	35
total	199,502	196,910	198,465	206,387	194,727

Table A.3: Net electricity generation (*GWh*) in Spain per year (2008-2013)

	year					
technology	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
hydro	22,935.5	26,186.4	41,833.8	30,437.3	20,653.6	37,385.4
reversible hydro	2,661.8	2,655.9	3,120.5	2,183.5	3,201.9	3,289.7
nuclear	56,460.3	50,549.4	59,242.3	55,005.9	58,595.4	54,210.8
coal	46,508.4	34,793	23,700.6	43,177.5	53,779.9	39,441.5
fuel+gas	9,887.6	9,276.3	8,821.7	7,007.9	7,094.6	6,563.8
combined cycle	93,197.5	80,223.8	66,799	53,430.9	41,074.4	27,569.9
hydropower	0	0	0	0	0	0
wind	32,159.8	38,252.8	43,545.4	42,477.3	48,524.5	54,713.4
solar *PV*	2,498	6,072.4	6,422.8	7,440.8	8,202.3	8,327.3
CSP	15.4	129.8	691.6	1,861.6	3,447.5	4,441.5
other renewables	2,078.4	2,516.4	2,459	3,714	3,791.1	4,334.3
cogeneration	24,222.6	26,001	28,110.7	30,593.3	32,444.3	30,835.7
non-renewable waste	2,485.6	2,623	2,970.8	1,287.8	1,589.4	1,617.2
renewable waste	782.6	793.1	808.5	736.1	719.8	555.7
total	295,893.5	280,073.3	288,526.7	279,353.9	283,118.7	273,286.2

Table B.4: Net electricity generation (*GWh*) in Spain per year (2014-2018)

	year				
technology	**2014**	**2015**	**2016**	**2017**	**2018**
hydro	33889	28382.6	36114.9	18450.6	34117.2
reversible hydro	3416	2895.4	3134.3	2249	1994
nuclear	54781.3	54661.8	56021.7	55539.4	53197.6
coal	41951.8	52616.5	37313.8	45019.4	37276.8

fuel+gas	5776	6483.8	6754.6	7001.6	6682.9
combined cycle	24828.8	29027.3	29006.5	37065.8	30044.5
hydropower	0.9	8.2	17.9	20.2	23.7
wind	45935.6	48117.9	47696.7	47907	49581.5
solar *PV*	8207.9	8243.6	7977.5	8397.8	7766.2
CSP	4958.9	5085.2	5071.2	5348	4424.3
other renewables	3816.3	3432.6	3425.7	3610.3	3557.4
cogeneration	24153.2	25200.9	25908.6	28211.8	29006.8
non-renewable waste	1965.9	2480.1	2607	2608	2435
renewable waste	678.1	818	785.4	877	874.1
total	254359.7	267453.9	261835.8	262305.9	260982

Table B.5: Capacity installed (*MW*) in California per year (2008-2013)

	year					
technology	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
coal	398	403	408	295	240	240
petroleum coke	173	173	173	149	36	36
biomass	1,084	1,098	1,086	1,156	1,182	1,217
geothermal	2,598	2,648	2,648	2,648	2,703	2,705
nuclear	4,456	4,456	4,577	4,647	4,647	2,393
natural gas	41,149	43,371	43,953	43,913	44,528	47,084
large hydro	12,074	12,074	12,105	12,145	12,145	12,155
small hydro	1,749	1,756	1,745	1,744	1,756	1,756
solar *PV*	7	15	117	228	780	3,118
CSP	400	408	408	408	408	925
wind	2,462	2,728	3,183	3,992	4,967	5,785
waste heat	52	52	52	52	52	52
oil	575	553	509	349	351	351
total	67,177	69,735	70,964	71,726	73,795	77,817

Table B.6: Capacity installed (*MW*) in California per year (2014-2018)

	year				
technology	**2014**	**2015**	**2016**	**2017**	**2018**
coal	132	93	55	55	55
petroleum coke	36	36	36	36	36
biomass	1,301	1,292	1,312	1,318	1,274
geothermal	2,703	2,716	2,694	2,694	2,730
nuclear	2,393	2,393	2,393	2,393	2,393
natural gas	46,185	44,527	42,475	42,223	41,491
large hydro	12,244	12,252	12,252	12,254	12,254
small hydro	1,756	1,751	1,750	1,758	1,756
solar *PV*	4,792	6,080	8,745	9,812	10,658
CSP	1,292	1,249	1,249	1,249	1,249
wind	5,847	5,680	5,645	5,678	6,004
waste heat	52	52	52	52	52
oil	352	352	352	352	352
total	79,085	78,473	79,010	79,874	80,304

Table B.7: Capacity installed (*MW*) in Spain per year (2008-2013)

	year					
technology	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
hydro	16,614	16,657	16,687	16,705	16,927	16,985
reversible hydro	2,451	2,451	2,451	2,451	2,451	2,451
nuclear	7,456	7,456	7,515	7,573	7,573	7,573
coal	11,325	11,325	11,342	11,572	11,064	11,079
fuel+gas	6,659	5,369	4,698	3,383	3,106	2,996
combined cycle	22,653	24,184	26,573	26,634	26,670	26,670
hydropower	0	0	0	0	0	0
wind	16,133	18,861	19,707	21,167	22,758	23,009
solar *PV*	3,351	3,392	3,829	4,233	4,532	4,638
CSP	61	232	532	999	1,950	2,299
other renewables	654	782	820	886	974	950
cogeneration	6,810	7,044	7,215	7,297	7,238	7,179

non-renewable waste	0	0	0	0	0	0
renewable waste	0	0	0	0	0	0
total	94,167	97,753	101,369	102,900	105,243	105,829

Table B.8: Capacity installed (*MW*) in Spain per year (2014-2018)

	year				
technology	**2014**	**2015**	**2016**	**2017**	**2018**
hydro	16,992	17,029	17,033	17,030	17,049
reversible hydro	2,451	3,329	3,329	3,329	3,329
nuclear	7,573	7,573	7,573	7,117	7,117
coal	10,936	10,936	10,004	10,004	10,030
fuel+gas	2,996	2,490	2,490	2,490	2,490
combined cycle	26,670	26,670	26,670	26,670	26,284
hydropower	11	11	11	11	11
wind	23,028	23,004	23,050	23,131	23,589
solar *PV*	4,646	4,681	4,686	4,688	4,714
CSP	2,299	2,304	2,304	2,304	2,304
other renewables	987	882	870	872	879
cogeneration	7,169	6,154	5,966	5,802	5,729
non-renewable waste	0	508	496	496	490
renewable waste	0	160	160	160	160
total	105,758	105,731	104,642	104,104	104,175

APPENDIX C

Table C.1: *CSP* Projects in California

project name	year built	location	technology	turbine capacity (*MW*) gross/net	storage (hours)
Genesis Solar Energy Project	2014	Blythe	parabolic trough	250 / 250	none
Ivanpah Solar Electric Generating System (*ISEGS*)	2014	Primm	power tower	392 / 377	none
Kimberlina Solar Thermal Power	2008	Bakersfield	linear fresnel reflector	5 / 5	none
Mojave Solar Project	2014	Harper Dry lake	parabolic trough	280 / 250	none
Sierra SunTower (Sierra)	2009	Lancaster	power tower	5 / 5.	none
Solar Electric Generating Station I (*SEGS* I)*	1984	Dagget	parabolic trough	13.8 / 13.8	3[1]
Solar Electric Generating Station II (*SEGS* II)**	1985	Dagget	parabolic trough	33 / 30	none
Solar Electric Generating Station III (*SEGS* III)	1985	Kramer Junction	parabolic trough	33 / 30	none
Solar Electric Generating Station IV (*SEGS* IV)	1989	Kramer Junction	parabolic trough	33 / 30	none
Solar Electric Generating Station V (*SEGS* V)	1989	Kramer Junction	parabolic trough	33 / 30	none
Solar Electric Generating Station VI (*SEGS* VI)	1989	Kramer Junction	parabolic trough	35 / 30	none
Solar Electric Generating Station VII (*SEGS* VII)	1989	Kramer Junction	parabolic trough	35 / 30	none
Solar Electric Generating Station VIII (*SEGS* VIII)	1989	Harper Dry Lake	parabolic trough	89 / 80	none
Solar Electric Generating Station IX (*SEGS* IX)	1990	Harper Dry Lake	parabolic trough	89 / 80	none

** and ** were dismantled and transformed into photovoltaic plants*

[1] Damaged in 1999 and not replaced

Table C.2: *CSP* Projects in Spain

project name	**year built**	**location**	**technology**	**turbine capacity (*MW*) gross/net**	**storage (hours)**
Andasol-1 (AS-1)	2008	Aldeire, Granada	parabolic trough	50 / 49.9	7.5
Andasol-2 (AS-2)	2009	Aldeire, Granada	parabolic trough	50 / 49.9	7.5
Andasol-3 (AS-3)	2011	Aldeire, Granada	parabolic trough	50 / 50	7.5
Arcosol 50 (Valle 1)	2011	San José del Valle, Cádiz	parabolic trough	49.9 / 49.9	7.5
Arenales	2013	Morón de la Frontera, Sevilla	parabolic trough	50 / 50	7
Aste 1A	2012	Alcázar de San Juan, Ciudad Real	parabolic trough	50 / 50	8
Aste 1B	2012	Alcázar de San Juan, Ciudad Real	parabolic trough	50 / 50	8
Astexol II	2012	Olivenza, Badajoz	parabolic trough	50 / 50	8
Borges Termosolar	2012	Les Borges Blanques, Lleida	parabolic trough	25 / 22.5	none
Casablanca	2013	Talarrubias, Badajoz	parabolic trough	50 / 50	7.5
Enerstar (Villena)	2013	Villena, Alicante	parabolic trough	50 / 50	none
Extresol-1 (EX1)	2010	Torre de Miguel	parabolic trough	50 / 50	7.5

		Sesmero, Badajoz			
Extresol-2 (EX2)	2010	Torre de Miguel Sesmero, Badajoz	parabolic trough	49.9 / 49.9	7.5
Extresol-3 (EX3)	2012	Torre de Miguel Sesmero, Badajoz	parabolic trough	50 / 50	7.5
Gemasolar Thermosolar Plant	2011	Fuentes de Andalucia	power tower	19.9 / 19.9	15
Guzmán	2012	Palma del Río, Córdoba	parabolic trough	50 / 50	none
Helioenergy 1	2011	Écija, Sevilla	parabolic trough	50 / 50	none
Helioenergy 2	2012	Écija, Sevilla	parabolic trough	50 / 50	none
Helios I	2012	Puerto Lápice, Ciudad Real	parabolic trough	50 / 50	none
Helios II	2012	Puerto Lápice, Ciudad Real	parabolic trough	50 / 50	none
Ibersol Ciudad Real	2009	Puertollano, Ciudad Real	parabolic trough	50 / 50	none
La Africana	2012	Posadas, Córdoba	parabolic trough	50 / 50	7.5
La Dehesa	2011	La Garrovilla, Badajoz	parabolic trough	49.9 / 49.9	7.5
La Florida	2010	Badajoz, Badajoz	parabolic trough	50 / 50	7.5

La Risca (Alvarado I)	2009	Alvarado, Badajoz	parabolic trough	50 / 50	none
Lebrija 1 (LE-1)	2011	Lebrija, Sevilla	parabolic trough	50 / 50	none
Majadas 1	2010	Majadas de Tiétar, Cáceres	parabolic trough	50 / 50	none
Manchasol-1 (MS-1)	2011	Alcazar de San Juan, Ciudad Real	parabolic trough	49.9 / 49.9	7.5
Manchasol-2 (MS-2)	2011	Alcazar de San Juan, Ciudad Real	parabolic trough	50 / 50	7.5
Morón	2012	Morón de la Frontera, Sevilla	parabolic trough	50 / 50	none
Olivenza 1	2012	Olivenza, Badajoz	parabolic trough	50 / 50	none
Orellana	2012	Orellana, Badajoz	parabolic trough	50 / 50	none
Palma del Río I	2011	Palma del Río, Córdoba	parabolic trough	50 / 50	none
Palma del Río II	2010	Palma del Río, Córdoba	parabolic trough	50 / 50	none
Planta Solar 10 (PS10)	2007	Sevilla	power tower	11.02 / 11	1
Planta Solar 20 (PS20)	2009	Sanlúcar la Mayor, Sevilla	power tower	20 / 20	1
Puerto Errado 1 (PE1)	2009	Calasparra, Murcia	linear fresnel reflector	1,4 / -	none
Puerto Errado 2 (PE2)	2012	Calasparra, Murcia	linear fresnel reflector	30 / 30	0.5

Solaben 1	2013	Logrosán, Cáceres	parabolic trough	50 / 50	none
Solaben 2	2012	Logrosán, Cáceres	parabolic trough	50 / 50	none
Solaben 3	2012	Logrosán, Cáceres	parabolic trough	50 / 50	none
Solaben 6	2013	Logrosán, Cáceres	parabolic trough	50 / 50	none
Solacor 1	2012	El Carpio, Córdoba	parabolic trough	50 / 50	none
Solacor 2	2012	El Carpio, Córdoba	parabolic trough	50 / 50	none
Solnova 1	2009	Sanlúcar la Mayor, Sevilla	Parabolic trough	50 / 50	none
Solnova 3	2009	Sanlúcar la Mayor, Sevilla	parabolic trough	50 / 50	none
Solnova 4	2009	Sanlúcar la Mayor, Sevilla	parabolic trough	50 / 50	none
Termesol 50	2011	San José del Valle, Cádiz	parabolic trough	49.9 / 49.9	7.5
Termosol 1	2013	Navalvillar de Pela, Badajoz	parabolic trough	50 / 50	9
Termosol 2	2013	Navalvillar de Pela, Badajoz	parabolic trough	50 / 50	9