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Economics from the Nova School of Business and Economics.

The Impact of Utility-Scale Solar PV Power Plants on Ecosystem Services: A Contribution to
the Portuguese Case

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Abstract (100 words maximum)

As renewable energies are gaining more importance, this paper presents the impact of solar photovoltaic power plants on ecosystem services in Portugal. Utility-scale solar photovoltaic plants are land-use intensive and generate multiple impacts on the environment. This analysis estimates the consequences of solar PVs on different ecosystem services and their contribution to the social benefit. We estimate and map the economic values of four land based different ecosystem services prior and post the installation of utility-scale solar PVs.

Keywords (Ecosystem Services, Solar PV Power Plants, Environment, Renewable Energy)

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1 Introduction

Renewable energies are gaining importance with the focus on reducing on GHGs emissions to preserve the condition of natural ecosystems of our planet. The European Union is pursuing a goal of achieving 45% of energy from renewable sources for the by 2030 (European Commission). Solar energy is one of the leaders in the field of renewable energies, as prices have significantly decreased in the last years. Consequently, some countries with significant exposure to solar radiation have the privilege and opportunity to exploit this resource, not only to reduce their CO₂ emissions but additionally to gain control over electricity prices and reduce their energy dependence (Lopez-Doriga, 2022).

In Portugal solar energy (utility scale and decentralized) is currently responsible by 8.2% of total energy supply, with the target of 80% of supply by 2030 being from renewable energy only (Silva and Sareen, 2021; Sousa, 2022). In the context of the current energy crisis in Europe, Portugal has an advantage due to its geographic position and its exposure to the sun light, allowing for the country to reduce its fossil fuels consumption and gain independence in the energy sector (Electric Summit, 2022).

However, solar photovoltaic plants being land use intensive can lead to other consequences on the environment that are rarely considered when designing renewable energy plans. Previous assessments have signaled different environmental impacts due to the fact that solar utility-scale PV powerplants are land-intensive and will be used for that purpose often for decades (typically 30 years). However, the assessment of the negative externalities that results from their deployment is still rare in the literature. Some of the reported consequences are natural habitat loss, biodiversity degradation, impact on climate change, as well as on recreational resources and soil erosion (Kim & al., 2021; Pimentel Da Silva and Branco, 2018; Turney and Fthenakis, 2011). Hence, the question of whether a balanced trade-off between decreasing gas

emissions and the potential damages in the ecosystem services delivery is timely and should be properly analyzed.

In the present study, this assessment is undertaken, namely, by examining the consequences to the provision of ecosystem services associated to the land occupation by solar PV utility-scale power plants. In other words, the opportunity cost of land cannot be ignored. To this end, we use the results obtained from a meta-analysis that was conducted for the Portuguese territory, which has estimated the economic value of land-based ecosystem services. The main purpose of this study is then to understand how solar power plants affect different location-specific ecosystem services, in order to obtain an estimate of the net social benefit associated to their deployment.

The results of this analysis provide a first overview of the impact of utility-scale solar PV power plants on four different ecosystems in Portugal. The analysis provides evidence of positive, neutral and negative impacts of solar utility scale PV power plants on ecosystem services and allows to estimate the net social benefit associated to their deployment.

The remainder of the paper is organized as follows. Section 2 provides a brief literature review on the topic. Section 3 presents the Portuguese case study including the methodology followed in this paper. Additionally, section 4 presents the results obtained and section 5 offers some discussion. Finally, section 6 concludes.

2. Literature Review

2.1 Ecosystem Services

Our modern world is dependent on what nature can provide to us. However, the degradation of biodiversity is progressing fast all over the planet due to uncontrolled human activities.

The Gretchen Daily (2016) defines Ecosystem Services as: *“the conditions and processes through which natural ecosystems and species that make them up, sustain and fulfill human*

life". The emerging discussions and concerns about the degradation of the environmental asset (natural capital) is supported on the facts showing that over half of ecosystem services of the world have been degraded and used in an unsustainable way (Tallis and Kareiva, 2005). Therefore, it is time for ecosystem services to be considered in policy decisions making (Tallis and Kareiva, 2005). The ES, given their public goods features were for a long time considered as "free", thus falling outside the scope of markets, thus being invisible (Chee, 2004). In other words, it was as if the opportunity cost of using the natural areas was zero, which contributed to the degradation of those areas and of the quality of the ecosystem goods and services provided. As a consequence, they were systematically ignored for public policy purposes.

The main purpose of The Economics of Ecosystems and Biodiversity (TEEB) is to draw attention to this issue and initiate a visualization and valuation of natural capital. The main challenges of TEEB are the subjectivity and incommensurability (Sukhdev & al., 2014). Considering the knowledge gap regarding the consequences of ecological processes for biodiversity and emerging discussions regarding biodiversity conservation, TEEB argues that we should not wait to have access to perfect information as the future costs of inaction would be immoderate. A single valuation process does not exist, representing the main challenge of The Economics of Ecosystems and Biodiversity.

2.2 Solar energy

The global challenge of degradation of Ecosystem Services has brought attention to the role that renewable energies could play, in the sense of using the services in a sustainable way. With the arising consciousness and willingness to decrease carbon emissions as scientific evidence-based on climate change was made public, the focus on the energy sector was unavoidable as fossil fuels were increasingly made responsible for the observed environmental degradation.

The renewable energy market is however very intensive in land and resources, especially utility-scale solar power plants.

2.2.1 World context

Based on data from IRENA Renewable Cost Database 2021, it is possible to acknowledge the continuous increase in competitiveness of renewable energy vis-à-vis fossil fuels since 2010. Recently, this trend was reinforced due to the increase in the prices of fossil fuels in the context of the energy crisis.

The global weighted average levelized cost of electricity (LCOE) of newly commissioned utility-scale solar PV projects declined by 88% between 2010 and 2021, while onshore wind fell by 68%, Concentrating Solar Power (CSP) by 67% and offshore wind by 60%.¹ The levelized cost of electricity from solar PV fell by 13%, while onshore and offshore wind fell by 15% and 13%, respectively, compared to 2020. Almost two-thirds – or 163 gigawatts (GW) – of newly installed renewable power in 2021 had lower costs than the world’s cheapest coal-fired options in the G20, confirming the critical role of cost-competitive renewables in addressing today’s energy and climate crises. This is clear from the figure (Fig. S.3 appendix) where the weighted average LCOE of utility-scale solar PV is compared to fuel and CO₂ cost only for fossil gas in Europe for the period 2010-2022. The global weighted average capacity factor for new, utility-scale solar PV increased from 13.8% in 2010 to 17.2% in 2021. This change results from the combined effect of evolving inverter load ratios, a shift in average market irradiance and the expanded use of trackers – driven largely by increased adoption of bifacial technologies – that unlock solar PV’s use in more latitudes.

At an individual country level, the weighted average LCOE of utility-scale solar PV declined

¹ The levelized cost of electricity (LCOE) is the most used indicator to assess competitiveness between the different energy producers. It is the

by between 75% and 90% between 2010 and 2021. Solar PV capacity grew about 21-fold between 2010 and 2021, with over 843 GW installed by the end of 2021.

Recent Market trends

By the end of 2021, over 843 GW of solar PV systems had been installed, worldwide. This is almost 21-fold growth for the technology since 2010. About 133 GW of newly installed systems was commissioned during 2021 alone (13% more than in 2020). These new capacity increases were the highest among all renewable energy technologies that year. Asia has led new solar PV installations since 2013. In 2021 Asia contributed with about 57% of all new installations, namely by China which accounted for around 70% of all new Asian (and about a 40% of all global) installations. During 2021, PV installations in India more than doubled compared to 2020. Indeed, taken together, India, Japan and the Republic of Korea contributed another 18.3 GW of new PV capacity in 2021 (a 37% increase on 2020).

Historical markets outside Asia also continued to gain scale. Compared to 2020, new capacity in the United States increased by more than a third. During 2021, the United States, Brazil and Germany together installed about 30 GW, while Spain and the Netherlands exceeded 3 GW each in new installations. The global weighted average LCOE of utility-scale PV plants decreased by 88% between 2010 and 2021, from USD 0.417/kWh to USD 0.048/kWh. This 2021 estimate also represents a 13% year-on-year decline from 2020. Globally, too, the range of LCOE costs continues to narrow. In 2021, the 5th and 95th percentile of projects ranged from USD 0.029/kWh to USD 0.120/kWh, representing 86% and 77% declines on the 5th and 95th percentile values, respectively, in 2010. After remaining flat during 2018 and 2019, the 5th percentile value declined 17% between 2019 and 2020, to reach USD 0.038/kWh. Between 2020 and 2021, the decline was much stronger, at 23%. In 2020, the 95th percentile value remained flat in relation to its value in 2019 but declined 26% between 2020 and 2021 (Figure

3.7 in appendix). The rapid decline in total installed costs, increasing capacity factors and falling O&M cost have contributed to a remarkable reduction in the cost of electricity from solar PV and its improving economic competitiveness. The downward trend in the LCOE of utility-scale solar PV by country is presented in Figure 3.9 in the appendices. Analysis of markets where historical data is available going back to 2010 shows that between then and 2020, the weighted average LCOE of utility-scale solar PV declined by between 75% and 90%, depending on the country. The lowest weighted average LCOE in the utility-scale sector could be observed in China, where between 2010 and 2021, costs declined by 89%, to reach USD 0.034/kWh – a value 29% lower than the global weighted average for that year, as reported in Figure 3.8 (appendix). After China, India achieved the most competitive LCOE in 2021, with a value of USD 0.035/kWh (just 2% above the value in China).

The remarkable, sustained and dramatic decline in the cost of electricity from utility-scale solar PV is observed in the power generation sector's evolution over the past decade. Since 2010, the solar PV industry has seen a variety of technological developments that have contributed to improvements in the competitiveness of the technology. These have occurred along the whole solar PV value chain. From the increased deployment of larger polysilicon factories and improved ingot growth methods to the increased ascendancy of diamond wafering methods and the emergence and dominance of newer cell architectures, the PV industry is constantly seeing innovations. Solar PV module costs have declined so rapidly now that new solar PV markets have emerged, globally. Between 2010 and 2021, those cost declines contributed 45% to the LCOE reduction of utility-scale PV (Figure B3.3 in appendix). The costs of other hardware components have also declined during the period. Indeed, taken together, cost reductions in inverters, racking and mounting, and other BoS hardware contributed another 17% to the LCOE reduction during the 2010 to 2021 period.

As solar PV technology has matured, the relevance of BoS costs has also increased. This is

because module and inverter costs have historically decreased at a higher rate than non-module costs, increasing the share of total installed costs taken by BoS (IRENA, 2018). Engineering, procurement and construction (EPC), installation, and development costs, when combined with other soft costs, were responsible for 26% of the LCOE decline over the 2010 to 2021 period. The rest of the reduction can be attributed to: improved financing conditions as markets have matured; reduced O&M costs; and an increased global weighted average capacity factor, driven by a shift to sunnier markets, between 2010 and 2013.

As the efficiency of solar PV modules increases, less surface area to generate a given quantity of power is needed with impact on land use. Land availability issues are very important in solar field array deployment. If flexibility is available uniform arrays of square or rectangular shapes can be installed, implying that less land area is needed. If the shape does not obey to any specific form, land use efficiency decreases, as some boundary curves or slopes may result in less efficient placement, from a land-use perspective. Moreover, from an economic point of view in places where the land where land is relatively cheaper, there is less needed to optimize panel location for energy capture. Its impact can be seen in the wide range of values in hectares (ha)/MW shown in Figure B3.4 in the Appendix, which also highlights the module efficiency trend. The figure shows a decline of 62% between 2010 and 2021, from 2.69 ha/MW to 1.94 ha/MW, in the amount of land used by PV projects to generate each MW.

2.2.2 The Portuguese case

Portugal is one of the countries with longest exposure to the sunlight in Europe, with a daily average of sun light of 430'000 GWh equivalent to the energy used by the country in 1000 days (Figueira, 2020). Due to its privileged geographic location in terms of solar radiation Portugal has clear advantages compared to other EU members to its realization of renewable energy plans (Jorge, 2020).

Moreover, as reported above, the decrease trend in prices that was observed more globally was not an exception in Portugal. The solar energy benefited from Feed-in-Tariffs that were considered the most successful mechanism in promoting this technology. Under these circumstances and given the Portuguese government plans to produce green hydrogen at Sines, solar PV utility scale investments have increased very significantly in the last two years and will keep increasing as they become even more competitive. The auctions for injection points in the grid to produce solar energy launched by the government in 2019 were very successful obtaining a record price of 20 euros per MWh, and an absolute record low of around 14.5 euros per MWh. The last political events in Europe have changed the economic conditions with an impact on the funding conditions for those projects. Consequently, the government has decided to adjust the prices by the inflation rate to avoid jeopardizing future investments.

The target set is to supply 80% of energy demand from renewable sources by 2030. To this end, the expansion of solar energy to 9 GW (Silva and Sareen, 2021) is proposed. This is stated in the PNEC 2030 which was delivered by the Portuguese Government to the EU in December 2019 with the expected renewable energy forecasts until 2030. The solar energy is planned to be provided through solar PV panels in residential sectors, floating PVs installed on seven different dams of the country and deployed in-land intensive PV utility-scale power plants.

To promote a low carbon transition and achieve carbon neutrality by 2050, Portugal doubled its total solar capacity in power plants between 2020 and 2022. In 2022 the solar energy supply was around 8.2% of total supply of electricity in the country, allowing for Portugal to save 1528 million euros in natural gas imports and 3.4 million tons of CO₂ in the first 5 months of the 2022 year (Sousa, 2022). Therefore, solar energy plays a key role in the Portuguese energy plan.

This paper focus on utility scale photovoltaic plants in Portugal. Photovoltaic systems convert solar energy directly into electricity through a photovoltaic effect. Certain materials present in

the photovoltaic cell panels are capable of absorbing photons and release electrons creating an electric current (Iberdrola). A recent decline in the cost of solar PV panels increased significantly solar energy market competitiveness (Guerin, 2017).

Photovoltaic plants based on land have some advantages, such as zero emissions of greenhouse gas and most importantly their price has been decreasing very significantly throughout the years. Moreover, they do not produce noise pollution in contrast to wind turbines. The main challenges regarding the management of solar energy are licensing and storage of this energy (Coelho, 2022). However, its impact on the location-specific land and environment where it is deployed has yet to be assessed.

2.3 Environmental impacts of solar power plants

Renewable energies systems cannot be considered as perfectly sustainable for the Ecosystem Services conservation, as the installation causes recurrently biodiversity losses. Only a few studies consider the consequences of deploying solar power plants on the land. Originally, the pollution derived from the fabrication of solar plants cannot be ignored, namely water resources pollution, emissions of air pollutants or the use of hazardous contaminates (Tawalbeh & al., 2021). Although solar energy plants have zero emission of carbon during their operation cycle, this is not the case for their entire life cycle, that is, from production until decomposition (Tawalbeh & al., 2021).

Turney and Fthenakis (2011) identified in their research 32 different environmental impacts of solar PVs namely, land occupation, habitat fragmentation, soil erosion changes, visual pollution. Solar renewable energy is land use intensive. To implement solar PVs all the vegetation has to be removed depriving the local species of their natural habitat and causing soil erosion (Pimentel Da Silva and Branco, 2018). The impact on wildlife and biodiversity is strongly correlated with the type of land and its soil where the power plant will be installed

(Turney and Fthenakis, 2011). It is very common that renewable energy plans target only the reduction of greenhouse gas emissions, neglecting biodiversity conservation. Consequently, the trade-off between reducing carbon emissions and wildlife habitat conservation is not guaranteed (Kim & al., 2021).

Moreover, the use of land for installing solar PVs power plants also impacts negatively local populations, reducing cultivable land and affecting its management causing diamenities, such as visual pollution, as well as health risks from manufacture, bird mortality and chemical pollution of cleaning the solar panels (Pimentel Da Silva and Branco, 2018; Silva and Sareen, 2021; Tsoutsos & al., 2005).

The impact of those power plants on ecosystem services is still rarely estimated, despite the importance of the spillover effects between the deployment of renewable energy power plants and ecosystem services preservation (De Marco & al., 2014). As these authors highlight, the choice of the land where the PV power plants are to be installed typically disregards the ex-ante benefits of the ecosystem goods and services provided by that land.

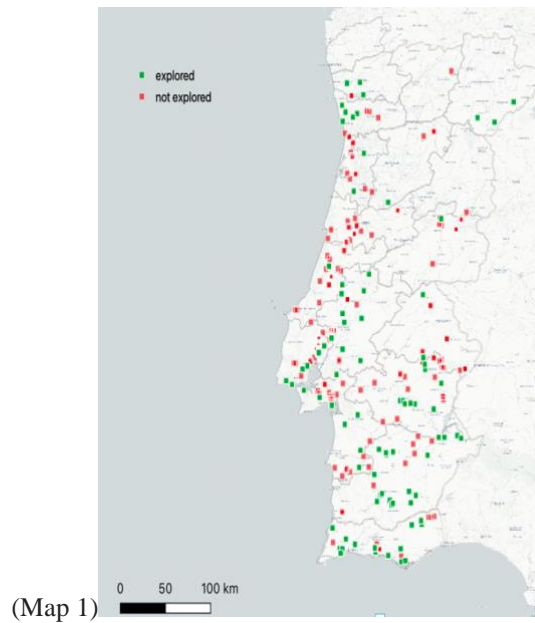
This paper aims to contribute to this literature by assessing the value of the land ecosystem services prior and post to the installation of utility-scale solar PV power plants in Portugal.

3.The Portuguese case study

This section illustrates the methodology followed to assess the economic value of in-land ecosystem services before and after the deployment of utility-scale solar PVs power plants in mainland Portugal.

A combination of two prior studies of the Environmental Economics Knowledge Center of Nova SBE was undertaken. For this purpose, a map with the exact coordinates of every in-land solar plant was produced, whether they were already producing or only licensed.

Map of deployed in-land utility-scale solar PV panels in continental Portugal



According to the map, (*Map 1*) we observe that 235 of them are not explored yet and are only licensed. This is the result of a recent decision of the Portuguese government, namely, to duplicate the production of energy using solar power plants, 132 power plants are currently in exploration. Therefore, to limit the study area and evaluate the impact of solar PVs on ecosystem services, the focus is on the solar plants that are already in exploration. Importantly, a major part of solar panels in exploration are situated in Alentejo. This can be due to the existence of a high natural endowment in this area, complemented by a low densely populated area, and, eventually, the fact that the project for the production of green hydrogen to which the Portuguese Government seems to be significantly committed is in the region of Sines, where the unique refinery is located, as well as one of the largest ports in EU and the most important in Portugal and one of the most important of the Iberian Peninsula.

3.1 Impact on Ecosystem Services

Different ecosystem services

Occupation of land can impact different ecosystem services. Seixo & al., (2021) focused on 7 of them: recreation, pollination, water purification, drought regulation, food supply, erosion prevention and climate regulation. Land occupation by solar parks leads to several impacts on ecosystem services. For the purpose of this study, the impact on 4 ecosystem services is considered, that is, on Food Supply, Recreation, Climate Regulation and Pollination.

Selection of ecosystem services

Food supply, part of provisioning services, is a product of raw material provided by ecosystem services. The difference between before and after the installation of solar panels on food supply will depend on the typology of the land and its likelihood to provide food. Recreation is a non-tangible benefit, classified as a cultural service, such as aesthetics, landscape amenities and the natural environment provided by nature. Recreation and Food supply are both expected to experiment some negative changes with the implementation of solar power plants on their land. As the solar PVs area is not accessible to the public and is often considered as visual pollution, the estimated values of the ES Recreation after the implementation of solar PVs are expected to decline. Regarding Food supply, the type of solar plants installed in Portugal do not allow any cultivation on the land under the solar panel, or at least it has not been implemented yet. Accordingly, the ES of food supply is expected to decrease as well. For both ecosystem services of food supply and recreation, a total loss was considered, implying the value of zero after the implementation of solar panels on the land.

On the other hand, Pollination and Climate Regulation are not proven to disappear with the deployment of solar panels. Pollination, mostly provided by insects, birds and bats, is a regulation ecosystem service. Multiple studies have proven of a positive impact of solar PVs on pollinators biodiversity conservation with appropriate solar parks management (Blaydes &

al., 2021). One of the roles of Climate regulation is the natural sequestration of CO₂ by the vegetation, meeting the main purpose of renewable energies. For this specific reason, estimating the impact of solar panels on the Ecosystem Services of Climate Regulation is essential to this analysis. The total impact on these two ecosystem services is unclear and therefore an estimation of their economic value is required. For this purpose, a meta-analysis that allows to estimate the total economic value provided by those ecosystems is appropriated. The method depends on the availability of studies and on the type of service. For this paper, the meta-analysis and market prices were used depending on the particular circumstances, and to this end the paper by Seixo & al., (2021) was used.

3.2 Methodology

Before the implementation of solar PVs

The estimation of the economic value of ecosystem services was entirely based on the results obtained by Seixo & al. (2021) in their estimation of land-based Ecosystem Services based on market prices and on the results of a meta-analytic benefit transfer function. In their estimation of land-based ES, market prices were used when available. Otherwise, the values of ES estimates of the revised studies were converted to a common metric and estimated using a meta-analytical benefit transfer function. In this paper, only the values regarding the ES of the land where the solar plants is/will be deployed (in exploration/licensed) are extracted.

To obtain the value of the location-specific ecosystem services of the land at stake, prior to the installation of solar PVs, a combination of the solar power plants map and the results of estimated land-based ecosystem services was used. Only the data regarding the ES values on the land of already explored or only licensed solar plants was selected. Allowing to extract the estimates of several land-based ES, prior the installation of utility-scale solar PVs power plants. Before the implementation of solar parks, in the data base, the land was considered as

agricultural and every estimation, in this part, of economic value of ecosystem services, was based on the assumption that the land was used for agricultural purposes.

After the implementation of solar PVs

Before the implementation of solar parks, in the original database, the land was under the category “Agricultural” and every valuation of ES was made based on this category. To estimate the values of the Ecosystem Services after the installation of solar PVs, a change *of the type of land* was introduced in the initial data base built in Seixo & al. (2021) being now classified as “Industrial”. This change allowed for computing new estimates of ES on the solar PVs territory after the installation of the panels. The change from the categories *Agricultural* to *Industrial* is aligned with the literature review that underlines the impossibility of using the vegetation and soil of the land once it is occupied by PVs with different consequences for Ecosystem Services.

To undertake in these new circumstances the valuation exercise, a combination of the new estimates corresponding to the value of ES of an industrialized land and our original map of solar plants in Portugal was produced and a new map was built. The results of the impact of solar plants on four Ecosystem Services (food supply, recreation, pollination and climate regulation) are mapped.

4.Results

After the estimation of the economic values of ES, the change in the estimated land economic values before and after solar PVs deployment, in Portugal, is illustrated in two different maps. It should be underlined that this analysis is mostly based on an estimation of the change in the data base obtained from a meta-analysis, by Seixo & al., (2021), of categories of the type of land, from Agricultural to Industrial. The estimates need to be carefully analyzed as they were

based on some important assumption (for ex. total loss for food supply and recreation) as well as some assumption, limitations that were initially present in data base from Seixo & al (2021) to build all the economic values estimates.

4.1 Pollination

ES Pollination before solar PVs

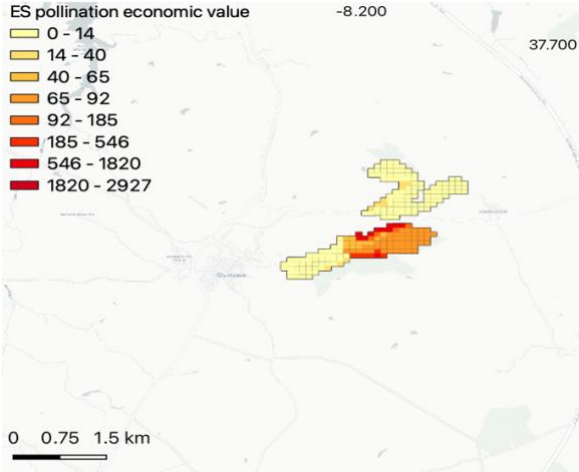


Figure 1

ES Pollination post solar PVs

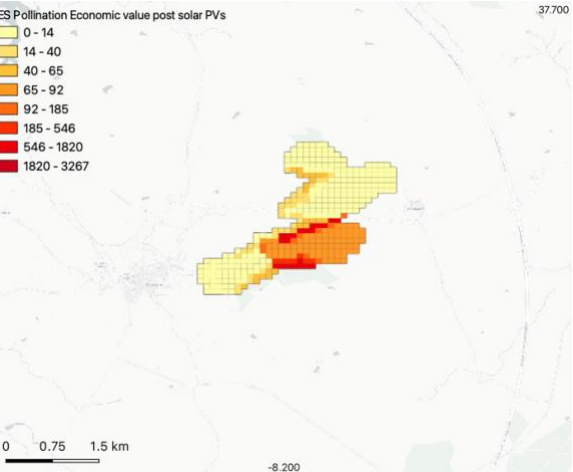


Figure 2

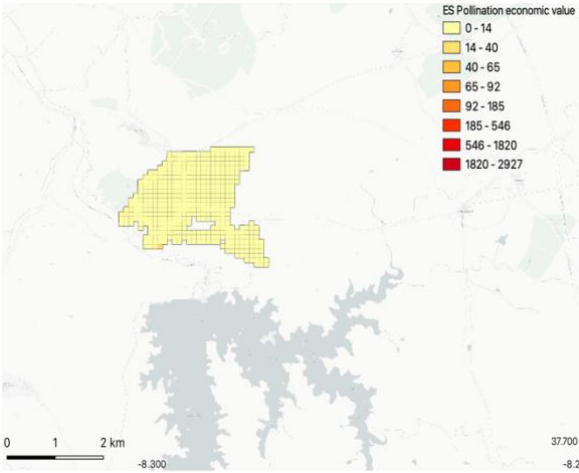


Figure 3

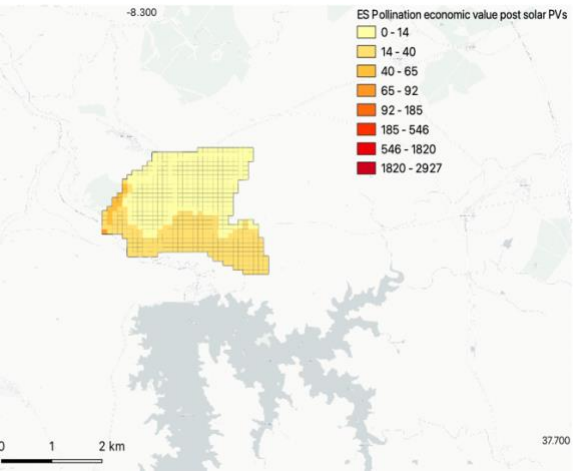


Figure 4

An increase of the ecosystem service of pollination is observed in most of solar parks after their deployment. Most of the solar parks experienced either an increase in economic value of Pollination or no change. This result underlines a potential positive impact of solar panels on the ecosystem services of pollination.

4.2 Recreation

ES Recreation before solar PVs

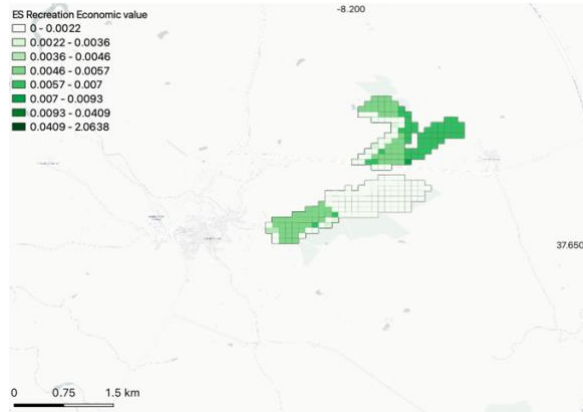


Figure 5

ES Recreation post solar PVs

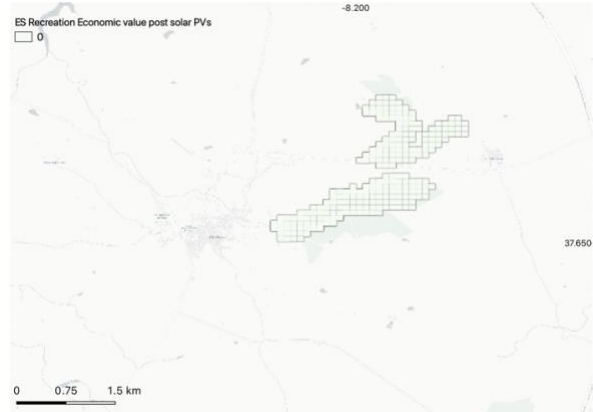


Figure 6

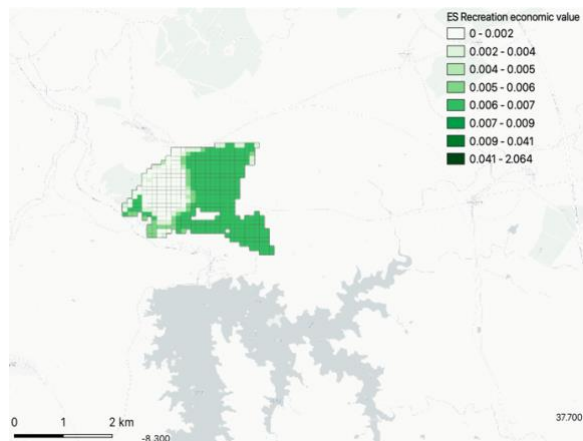


Figure 7

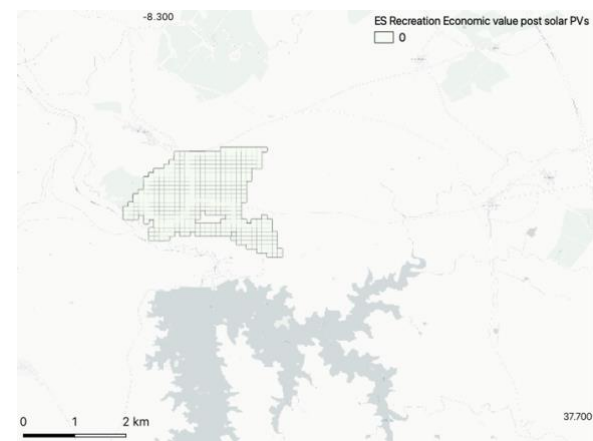


Figure 8

The consequences of solar parks on the Recreation are associated to a complete loss. The assumption is that as the land is occupied by solar panels it is no more available for recreation purposes. The low values concerning the ES of Recreation are due to the fact that they assess recreation value per person. To obtain the aggregate amount delivered to the population living around the area those values have to be multiplied by the average number of persons that visited and enjoyed Recreation services in this area in the last years, discounted to the current period.

4.3 Climate Regulation

ES Climate Regulation before solar PVs

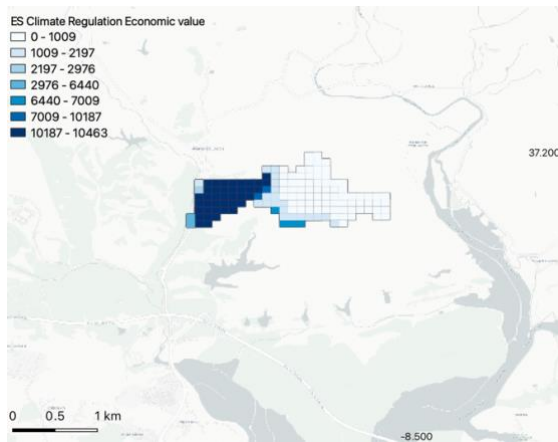


Figure 9

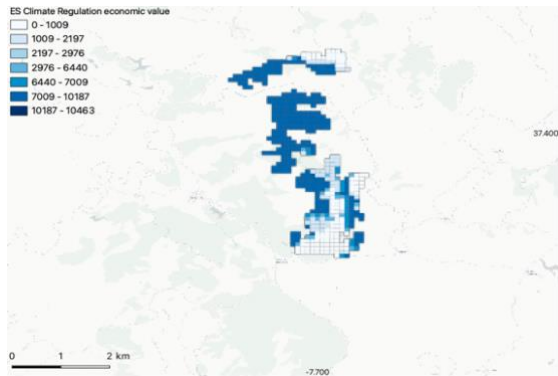


Figure 11

ES Climate Regulation post solar PVs

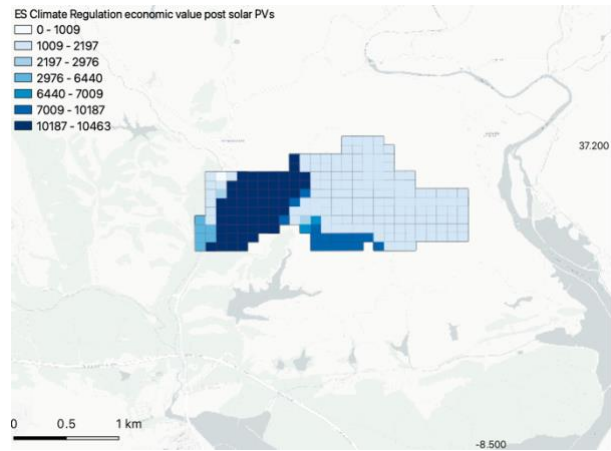


Figure 10

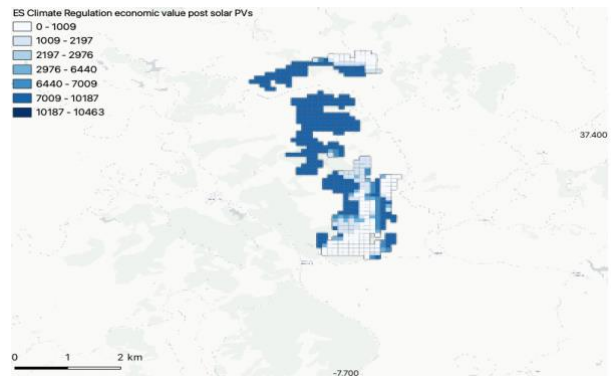


Figure 12

In the case of this specific solar park in Algarve contribute to an increase in the provision of Climate Regulation ES as it is clear from the maps. As some research papers underlined it, proper management of solar parks sites can enhance climate regulation. However, most of the estimation done in this study regarding the ES of Climate Regulation economic value after the implementation of solar panels showed no changes in the value of climate regulation, in comparison to the values prior the implementations of solar PVs.

4.4 Food supply

ES Food supply before solar PVs

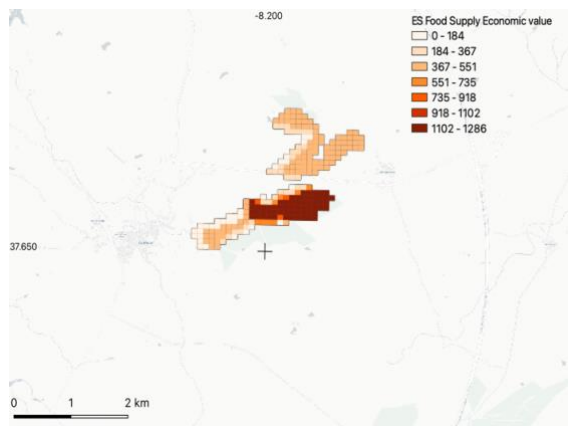


Figure 13

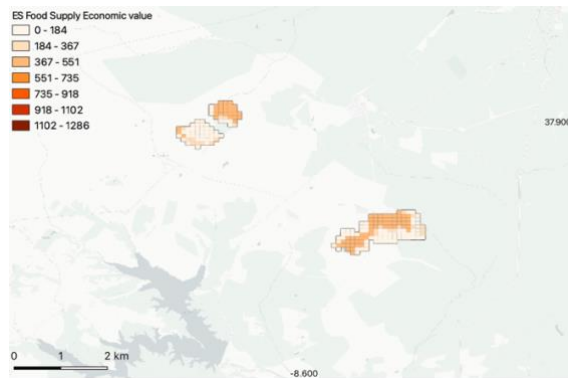


Figure 15

ES Food Supply post solar PVs

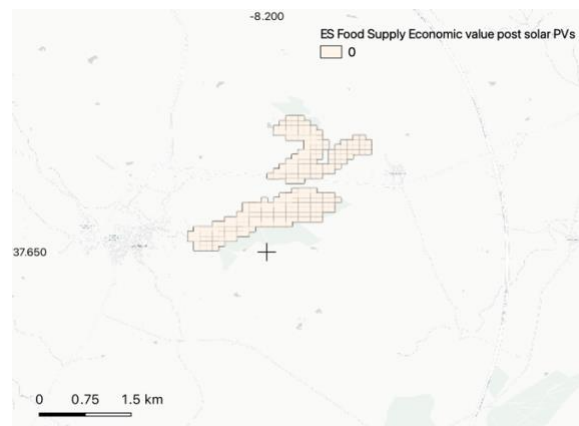


Figure 14

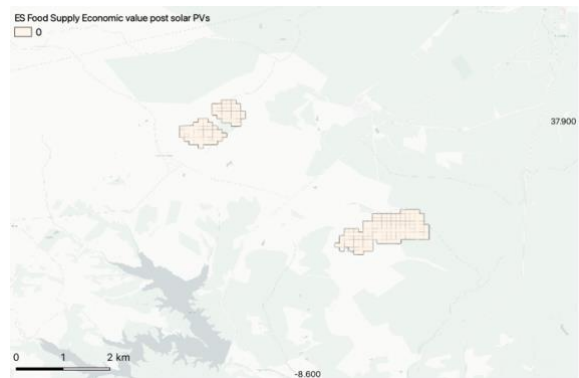


Figure 16

The estimated values for the ES of Food Supply reflect the agricultural patterns in Portugal. The value of Food Supply after the implementation of solar panels was set to 0 as a maximum loss. This is based on the assumption that once the land is occupied by solar panels, it is not possible to grow and cultivate food on it. This is mainly the consequence of solar panels in Portugal being deployed on the land directly, that is, not elevated from the land. However, as is reported in the literature the costs are much higher in this case.

5. Discussion

For the four ecosystem services analyzed in this study, two of them experienced at least in one location an increase while the other two suffered a full loss value loss.

The full loss of Food Supply and Recreation was mostly based on an assumption of land use change, which will make impossible the use of the land for any other purpose than solar plants. In most cases the solar plant is set on the ground, leaving no space between the installation and the earth. The natural environment that offers a non-material benefit is as well occupied. The installation of solar panels is enhancing the degradation of those two ecosystem services.

Concerning Climate Regulation, overall, the analysis leads to unclear results. Some of the locations show an increase in the value of ES of Climate Regulation. However, most of them seemed not to experience any impact. DeMarco & al., (2014) found in their paper a negative impact of solar PVs and therefore a lower contribution of vegetation to the ecosystem service of Climate Regulation. A hypothesis could be that if the land is dry and does not have much vegetation growing on it, the change in the ES of Climate Regulation might not be noticeable. It should be underlined that the overview of solar PVs panels on the ES of Climate Regulation is considerably poor in the literature and has yet to be explored.

Regarding the ES of Pollination, the estimated economic values seem to increase with the implementation of solar panels. This result is surprising but aligns with some studies in the literature Blaydes & al. (2021) underline the possibility of enhancing pollination in solar parks if deployed and managed strategically. Additionally, the decrease of pollinators is a challenge in agricultural land due to the use of pesticides. Since, solar facilities do not use pesticides, their land or surroundings could play a potential role of refuge for certain pollinators, explaining the increase of the ES Pollination economic value. (Dolezal & al., 2021). However, another paper brings attention to the fact that removing floral resources for solar parks will significantly reduce resources for pollinators unless there is a re-integration of native vegetation (Dolezal & al., 2021). It is important to consider the type of land and its original values in terms of ES Pollination as the values of the impact of solar PVs on pollination are different depending between different sites.

The decrease in certain Ecosystem Services values can be compared with the increase in others. The question whether the decrease of food supply ES can be compensated by the increase of pollination has to be analyzed. Our results suggest that not all the ES react in the same way to the implementation of solar parks. Moreover, the loss in ecosystem services values and the gain in CO₂ emission reductions must be considered. From a social perspective.

5.1 The optimal site selection

A proper location, type of land and valuation of Ecosystem Services is necessary to determine the ideal location for solar parks. Demarco & al. (2014) underline that 66% of solar plants are usually disposed in unsuitable areas leading to biodiversity decline. The understanding of the type of land where the photovoltaic plants are being deployed and its consequences on the ecosystems which surround them must be considered in the decision making process of solar parks deployment. The outcome of several studies focusing on solar power plants impact on the environment relates to the importance of an optimal site selection. Renewable energies are necessary however, so their implementation should be coordinated with the surrounding environment.

Moreover, solar panels have a life expectancy of approximately of 20 to 30 years and if there is no new solar project planned for the use of the land the question of recovery must be analyzed (Semeraro & al., 2018). The repercussions on ES caused by solar panels will lead mostly to an abandoned use of land with low economic value and degraded biodiversity (Semeraro & al., 2018). Consequently, the choice of the optimal site for utility scale solar PVs should consider the regeneration of the land post solar PVs. In the case of this study, after estimating different values of Ecosystem Services present on the land where the solar panels were introduced, the optimal site selection should consider a land with initially low ES values or one in which a loss in one ecosystem service can be compensated by an increase of another one.

5.2 Portuguese interest in solar energy

The rising interest in producing solar energy in Portugal is linked to its ambitious plans of production of green hydrogen. Green hydrogen is a technology based on the generation of hydrogen throughout a chemical process: electrolysis (Iberdrola). This process is very demanding in electricity and participate in the decarbonization of natural gas systems. Portugal's ambition is to become principal supplier of low-cost green hydrogen in EU by 2030. The solar power being low cost and abundant in Portugal compared to other Members States bringing an advantage to the country on the competitiveness level (Khatiwada & al. 2022). The interest of Portugal is not only to supply 80% of energy demand from renewable sources by 2030 but as well seize the opportunity of becoming a competitive leader supplier in green hydrogen. However, this ambition should not erase the importance of an optimal site selection to plant solar plants in order to preserve the ecosystem services.

5.3 Social benefit

Furthermore, the estimated values of ES prior and post solar PVs power plants deployment are compared using a simple equation of the Net Present Value of Social Benefit from the private perspective presents:

Net Present Value of Social Benefits (equation 1):

$$\begin{aligned} \text{PrivateReturns} = & \int_0^{T_1} R_A \cdot e^{-rt} dt + \int_{T_1}^{T_2} R_{PV} \cdot e^{-r(T_2-t)} dt + \int_{T_2}^{\infty} R_{A'} \cdot e^{-r(\infty-t)} dt + \\ & \text{avg CO2 savings yearly/ha in present value} \cdot (T_2 - T_1) + \text{compensations in eur} \cdot \\ & e^{-rT_1} - \text{avg ES Losses between } T_1 \text{ and } T_2 \text{ in present value} \cdot e^{-r(T_2-T_1)} \end{aligned}$$

The equation of the Net Present Value of Social Benefit from the private perspective presents:

- $\int_0^{T_1} R_A \cdot e^{-rt} dt$ the rent per year per hectares for the land used for agriculture, or alternative purposes, until T_1 which is the time where we switch to the implementation of solar PVs panels, discounted to present value by e^{-rt}
- $\int_{T_1}^{T_2} R_{PV} \cdot e^{-r(T_2-t)} dt$ shows the rent obtained during the time of exploitation of solar PVs: from T_1 until T_2 . T_1 and T_2 representing the time horizon of solar panel use. The rent for solar PVs is discounted to present value by $e^{-r(T_2-t)}$
- $\int_{T_2}^{\infty} R_{A'} \cdot e^{-r(\infty-t)} dt$ is the rent obtained, after the solar PVs use, for alternative use of land. If the land used to be agricultural the new value of rent $R_{A'}$ will most likely be lower than the initial one R_A because of damages caused to the land from solar parks. It is discounted to present value by $e^{-r(\infty-t)}$
- *avg CO2 savings yearly/ha in present value* $\cdot (T_2 - T_1)$ an average price of carbon ton in present value terms is used and multiplied by the time frame $(T_2 - T_1)$. It represents the savings of CO2 per hectares per year.

Including the social part:

- *compensations in eur* $\cdot e^{-rT_1}$ is the compensation in euros and in present value terms, paid to the municipalities due to the reglementary framework to compensate for environmental impacts of the installation of utility-scale solar PV plants
- *-avg ES Losses between T_1 and T_2 in present value* $\cdot e^{-r(T_2-T_1)}$ is the average of ecosystem services losses for the period between T_1 and T_2 in present value terms

5.5 Alternative land use solutions

Some studies underlined the potential positive impact of solar panels on different ecosystem services if some modifications are applied. For example, McKuin & al. (2021) provide an overview of the impacts of solar PVs placed on water instead of land. One of the important

benefits driven by this procedure is to reduce evaporation losses of water. Moreover, if the solar panels are placed over a canal, their efficiency increases, thus avoiding all the consequences related to the use of land.

Another solution studied by Jain & al. (2021) to minimize the decrease in food supply caused by the land occupation by solar PVSs is to combine agriculture and renewable energies. The agrovoltaic system (APV) consists of installing the solar panels above the ground, allowing for the land underneath to be used for cattle raising or cultivations. Furthermore, the system provides shade and protection of the wind and natural hazards. It contributes to the decrease of the heat stress for the farmers working there, supports cattle and favor the plants yield (Jain & al.2021).

However, this system does not avoid the visual pollution of the landscape. APV systems are still in early development and are expensive.

If deployed strategically solar power plants could enhance pollinator biodiversity in agriculture landscapes (Blaydes & al. 2021). Blaydes & al. (2021) propose in their review management recommendations for solar parks that could strengthen the ecosystem of pollination. They underline some evidence-based solar PVs management recommendations to help decrease the pollination decline. Among the 10 recommendations resulting from their study, the authors suggest creating and maintain diversification in vegetation structure and to minimize the use of agrochemicals, generating a range of microclimates (Blaydes & al., 2021).

Other beneficial repercussions of solar panels were underlined in some other studies. Guoqing & al. (2021) deliver the first evidence of solar power plants generating a surface cool island effect which spreads beyond the land occupied.

6 Conclusion

In this paper the effect of utility-scale solar PV power plants deployment in four land-based ecosystem services (pollination, recreation, food supply and climate regulation) is analyzed. The results suggest that land-use intensive solar PVs negatively impact ecosystem services of food supply and recreation. In contrast, a positive impact on the ecosystem service of pollination in several locations post the implementation of solar PVs can occur. A neutral and in some cases a positive impact was observed on the ES of Climate Regulation. The estimated values are aligned with is found in the literature. The analysis revealed the importance of site selection to minimize ecosystem losses.

Moreover, this research shows that compensation between positive and negative impacts of solar PVs on ecosystem services can take place besides the savings that be obtained on CO₂ emissions by substituting fossil fuel energy sources. Therefore, all these effects, and in particular, the consequences to the provision of ecosystem services and their economic value should be accounted for to better inform sustainable public policy decision making concerning deployment of renewable energy sources.

This study focused on the Portuguese case where solar PV utility scale investments increased considerably over the last two years, based on different motivations such as the production of green hydrogen, reduction in GHGs emissions and increasing independence of the energy sector. The discussion of potential alternatives to combine preservation of ecosystems and deployment of renewable energy should be adequately incorporated into the government's plans. This is a first contribution to this discussion, Other important issues to be considered need to be carefully addressed, namely in what concerns environmental justice or how those investments affect different income groups in the population. This is left for future research.

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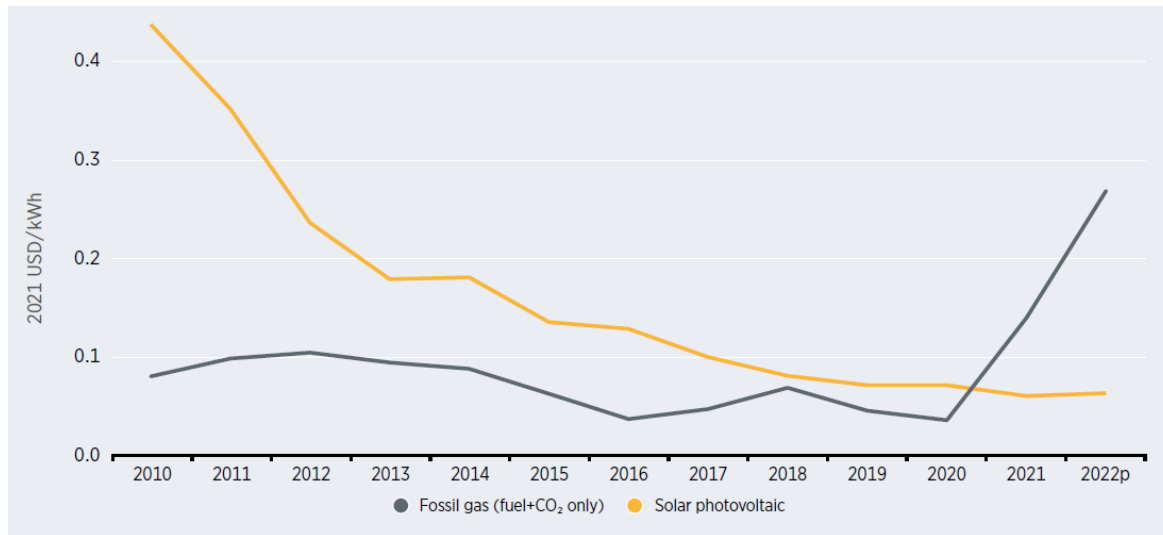
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Appendix

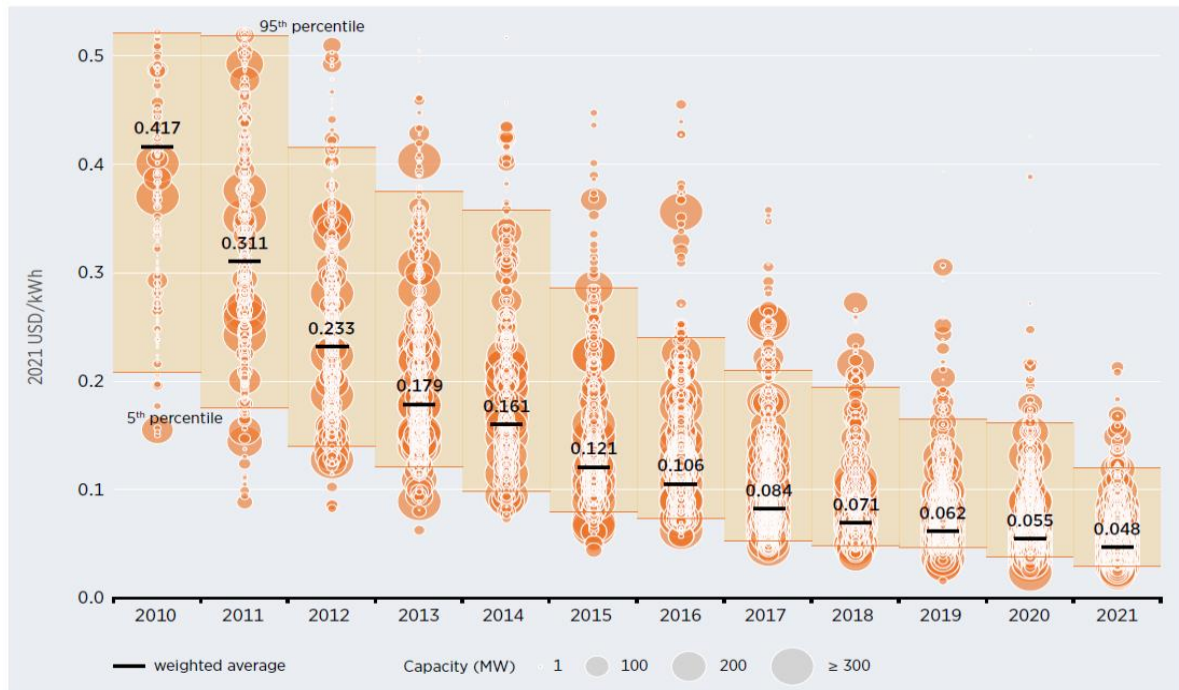
Tables corresponding to the section 2.2.1 provided from the IRENA Renewable Cost Database 2021 Report

Figure S.3 The weighted average LCOE of utility scale solar PV compared to fuel and CO₂ cost only for fossil gas in Europe, 2010-2022



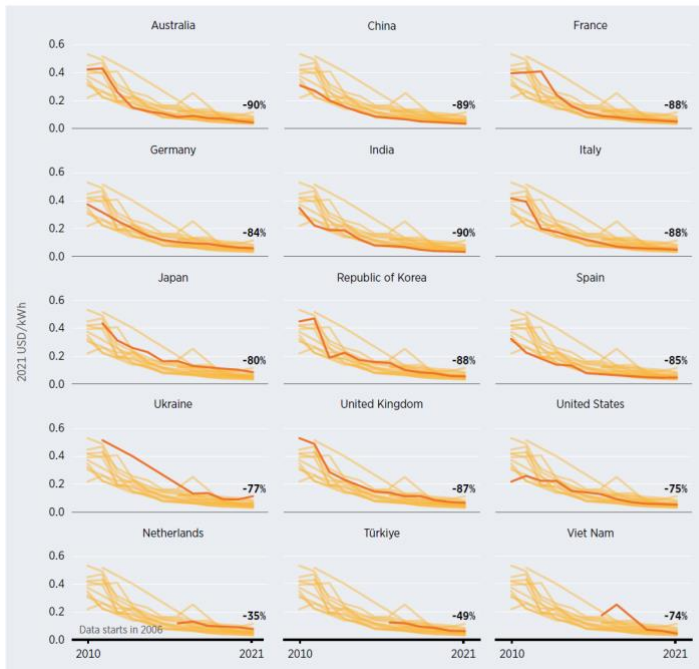
Note: 2022 values are possible outcomes for 2022 and not a forecast.

Figure 3.7 Global utility-scale solar PV project LCOE and range, 2010-2021



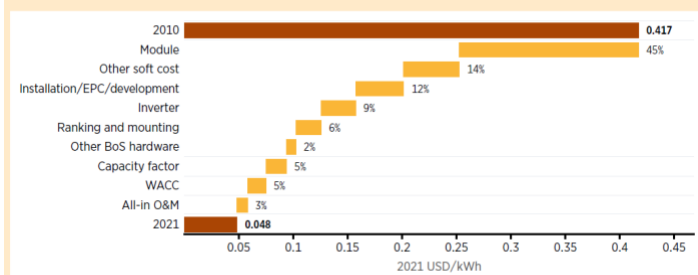
Source: IRENA Renewable Cost Database.

Figure 3.8 Utility-scale solar PV weighted average cost of electricity in selected countries, 2010-2021



Source: IRENA Renewable Cost Database.

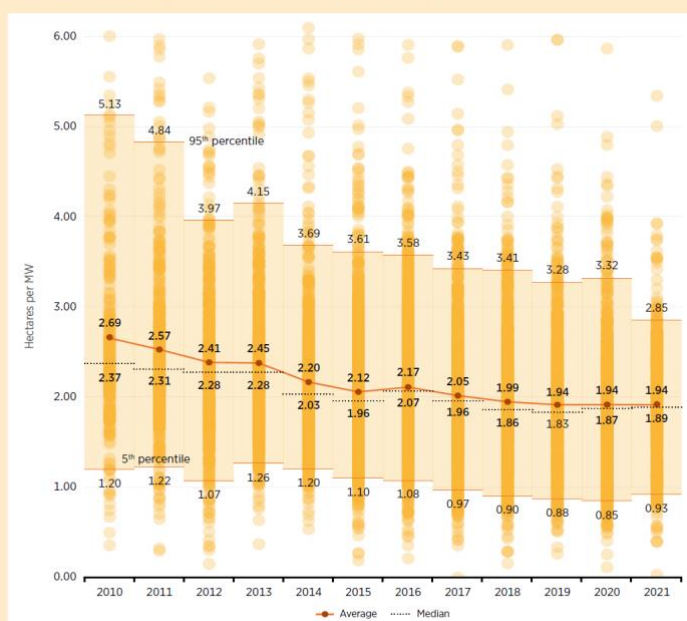
Figure B3.3 Drivers of the decline of LCOE of utility-scale solar PV (2010-2021)



Source: IRENA Renewable Cost Database.

Note: Percentage figures may not total 100 due to rounding up.

Figure B3.4 Global average utility-scale solar PV land use, 2010-2021



Source: IRENA Renewable Cost Database.