European Potential of Solar Technologies for Electricity Generation under Project Drawdown Framework

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Abstract

The emergency associated with climate crisis demands immediate action. All economic sectors need to decarbonize in order to fight Climate Change. The Power Sector is strategic whether it be by its massive contribution in greenhouse gases emissions or for its intrinsic capacity to decarbonize other energy-consuming activities in a transversal way. The Energy Transition era will be filled with various complex and interlinked challenges but, at least on the technological domain, there are good solutions to build a future energy mix that can combine security of supply, environmental protection, and economic performance both for investors and consumers. As part of Project's Drawdown regionalization phase in Europe, this work aims to collect several recent projections for the European Power Sector, from 2020 to 2050, in order to assess the contributions of solar powered solutions for electricity generation, namely, utility-scale PV (U-PV), distributed PV (D-PV) and Concentrated Solar Power (CSP), in terms of avoided GHG emissions, using Drawdown's model and methodology with 57 scenarios divided in 3 tiers of ambition. Results from this work project a 2050's European power sector characterized by a TAM size of (3,732 – 10,455 TWh/y) with U-PV adoption of (146 – 2,181 TWh/y), D-PV adoption of (93 - 901 TWh/y) and CSP adoption of (33 - 372). Together these solar solutions can abate (1.32 – 26,31 Gt CO_{2e}) and will demand investments of (233 – 2,230 billion €).

Keywords: *Solar Power; Long Term Projections; Greenhouse Gases Emissions; European Union; Drawdown; Renewable Energy*

1.Introduction

The newness of present times is that, maybe for the first time, technological development will be directed to address the consequences of our interference over the planet. Over the next decades huge efforts will be made in order to reduce the magnitude of impacts of Climate Change. Even a significant part of cultural production of the next future will be related to this goal. This will, most likely, define the times we live in and when future historians look back at the present, they may label it in a reference to the technological breakthroughs that allowed us to reduce the impacts of human development on the planet, the era of climate change and energy transition.

Climate Change is a transversal threat meaning that it will impact many different sectors of human life and economy. But reducing emissions is itself a transversal challenge since almost every human activity is a net emitter [1]. Looking at the bright side, it also means that there are also various opportunities to abate emissions across the entire economy.

As a matter of fact, some sectors are easier to decarbonize than others. This usually means having developed technological alternatives that can be scalable to substitute polluting old ones, preferably at competitive costs. Others still, are strategic in the sense that once they become carbon neutral many other activities that rely upon them will also reduce their carbon footprint. And some sectors should be prioritized due to its large share of emissions [2].

The power sector satisfies all these conditions. Is one of the biggest carbon emitters [3]. Renewable energy such as wind and solar power are already cost-competitive technologies and actually in many regions of the globe data acquired from newly power auctions suggest solar as being the cheapest form of electricity generation [4]. And with increased electrification many daily activities that once emitted GHGs would cease to pollute if power is supplied with carbon neutral mix. That is why the Climate Change Era should start with the Energy Transition Period.

The general purpose of this work is, primarily, to assess the potential of solar technologies for electricity generation to abate CO2e emissions from 2020 to 2050 at European level. There are some pre-requisites, that will serve as secondary objectives, such as: assessing the projected size in TWh of future European power market, the penetration of solar technologies in the 2050's European energy mix, the associated costs demanded by them. Then it is also necessary to size the individual contribution for each one of the solar technologies under analysis, namely, Utility-scale photovoltaic generation (U-PV), Decentralized photovoltaic generation (D-PV) and Concentrated Solar Power (CSP).

Moreover, it is important to highlight that this work is part of the Project's Drawdown regionalization process to focus over the many different regions of the globe, their differences, potential opportunities, deficiencies, and similarities. The creation of the Drawdown Europe Research Association (DERA) is a milestone in this process. Furthermore, this is the first time that Drawdown research is being developed as part of the fellowship program associated with the production of a master thesis.

2. Project's Drawdown Solar Solutions for Electricity Generation

Founded in 2014, Project Drawdown is a non-profit organization whose mission is to help the world stop global warming by reaching Drawdown. The project's name refers to the future point in time when levels of greenhouse gases in the atmosphere stop climbing and start to steadily decline. This is the point when we begin the process of stopping further climate change and averting potentially catastrophic warming. It is a critical turning point for life on Earth. Currently, the project is funded by individual and institutional donations [5].

To achieve Drawdown, the Project has shed light over many, if not every, aspects of the climate equation reducing sources - bringing emissions to zero, supporting sinks - uplifting nature's carbon cycle and improving the society - fostering equality for all. Nested within each action area, there are sectors and subgroups of different solutions. These solutions are based on practices and technologies that can help the world to stabilize and then start to reduce the levels of greenhouse gases in the atmosphere Together, they make up the Drawdown Framework for climate solutions, published in 2017 as the projects' inaugural work in print publication [1]. Although very the general scope of Project Drawdown is very broad, it is composed of a combination of smaller parts. This work will be part of the shifting production class of solutions aimed in replacing traditional fossil fuel-powered thermal plants for clean and environmentally friendly alternatives. Thus, this work is focused on solar based solutions for power generation, namely Concentrated Solar Power (CSP), Decentralized Solar Photovoltaics (D-PV) and Utility-Scale Solar Photovoltaics (U-PV).

3. Literature Review

Data sources for this work were not only from of authoritative agencies of the energy sector (International Energy Agency- IEA, International Renewable Energy Agency- IRENA), but also from other entities that deal with the reduction of GHG emission like the ones from ONG's (Greenpeace, Energy Watch Group – EWG, European Climate Foundation - ECF), or sectoral agencies (Solar Power Europe -SPE), Universities (LUT), technical reports for the European commission issued by Joint Research Centre (JRC) and oil companies (BP, Shell, Equinor). The reasoning is that by having a diverse pool of sources, it would prevent bias from over relying onto a single source, since many of these players are sometimes either too conservative or too ambitious in its projections with different set of assumptions and modelling constraints. Another important reason was to accommodate the results from a different set of model types used (bottom-up and top-down models, simulation, and optimization models, technologically detailed or of general equilibrium which might also result in significantly different expectations for technologies development in the long term.

Besides data relative to electricity generation and long-term pathways, other aspects are also of the interest in this work, such as market-oriented reports that are specialized in costs or technical aspects. In total, more than 50 publications have been researched, while looking for scenario projections and techno-economic data. A total of 53 different scenarios were identified, from which 37 of them were usable in the sense of having at least Total Addressable Market (TAM)[1] at European level[2]. These 37 scenarios were obtained from a set of 14 most useful reports. Table 1 lists all these 37 serviceable scenarios along with its 14 source documents, the issuing body and year of publication.

However, at this stage an important problem arises. There are many different interpretations of what Europe means. Some publications adopt "EU" or "EU28" labels, other prefer "OECD Europe" or "EU 31" or even just a generic "Europe". Few are versatile enough to offer different tables, one for "Europe" and another for "European Union" (WEO 2019 [6] from IEA has this approach). Thankfully, most publications maintain detailed information about what countries are included in its geographical groupings.

Whenever more than one definition was available "EU28" or "European Union" data was chosen. This option is justified by the political cohesion provided by the EU, and its willingness to become world leader in the Energy Transition and Climate Change action. The rationale behind any given geographical clustering must be the internal similarity of the countries composing the region relative to a given issue, and for solar energy European Union appears as the best choice available.

Another practical advantage of choosing a tighter geographical definition for Europe is the possibility of extracting data from other countries that do not belong to EU when they appear in certain publications. For instance, the Greenpeace's Energy Revolution [7] report form 2015 and Sven Teske's Achieving Paris Agreement Goals [8] form 2019 had a "OECD Europe", a grouping that included Turkey whereas both publications from LUT University, Full Study energy Transition Europe 2018 [9] and 100% Renewable Europe [10] have included both Turkey and Ukraine in its definition of Europe.

Before making any adjustments, publications with broader definitions of Europe tend to rank higher in projected values when scenarios were ordered, and comparison would not be fair nor adequate. The impact of including these two countries are noticeable and should be corrected. Initially GDP or another economic metric have been considered but then it was preferred to use some references with country-to-country data to proceed the removal.

Sven Teske's paper [8], one of the scenarios with "OECD Europe" label, offers a breakdown for load and generation for internal regions of Europe such as Iberian Peninsula, Nordic and also a specific one for Turkey detailed for the years 2020, 2030 and 2050. This data was used as proxy to assess the respective share of

[1] Total Addressable Market or TAM is the summation of all demanded functional units for a given region at a certain period. In this case, the size of the power market for electricity generation, in TWh, from 2020 to 2050.

[2] For the purposes of this work (pre-Brexit) European Union is formed by the following countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxemburg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden.

Turkey within this OECD Europe group that was then discounted both in the adoption as well as for TAM projections. The share seized by Turkey increases in time since it expected this country to grow more than the European average and are, respectively, 6.5%, 7.3 % and 8% for 2020, 2030 and 2050. Greenpeace Energy Revolution [7] report offers no similar way to do so, consequently, the same ratios from Sven Teske were applied to discount Greenpeace's projections for TAM and adoption of solar technologies.

The correction for scenarios that included both Ukraine and Turkey, the ones produced in association with LUT University [9], [10], suffered a similar process. The percentages for discount this time were based on SPE & LUT 100% Renewable Europe publication [10] that depicts electricity generation capacities in 2050 over a map with almost county to county resolution. A 15,5 % ratio, representing the contributions of Ukraine and Turkey, was discounted from TAMs and adoptions for these two references. All scenarios that have suffered adjustments for "geographical harmonization" are marked with an asterisk in Table 1. In the case of scenarios with the "EU31", as it happens in JRC publications [11], [12], the different grouping of European countries does not increase projections systematically. Objectively, the addition of Iceland, Norway, and Switzerland to the rest of EU28 gets diffused among other small variations in scenario projections and are too small to jeopardize the comparison with other scenarios.

Besides projections themselves, other important pieces of information are needed to properly run the Drawdown model. The economic variables are: First Costs per Implementation Unit, typically found in (€/kW), Fixed Operating and Maintenance Costs (FOM) also expressed in (€/kW), Variable Operating and Maintenance Costs (VOM) measured in (€/kWh). Technical parameters are "Lifetime Capacity" (h), "Average Annual Use" (h/y). All the data previously mentioned has been collected for all three solar technologies (*i.e.* U-PV, D-PV and CSP) and also for conventional thermal powerplants which the solutions are replacing. Fuel costs for each fossil have also been collected. Raw economic data is found in various different currencies but in order to serve as an input they were all corrected to 2014 USD. Economic results, however, were converted to 2019 Euros so as to better communicate values within the European context.

Most techno-economic data has been collected from sources like: Grantham Institute & Carbon Tracker Initiative's Expect the Unexpected 2017 [13]; ASSET Technology Pathways in Decarbonization Scenarios 2018 [14]; JRC Cost Development of Low Carbon Energy Technologies 2018 [15]; Guidehouse Gas Decarbonization Pathways 2020 [16]; REN21 Renewable Global Status Report 2020 [17]; IRENA Renewable Energy Statistics 2019 [18]; IRENA Renewable Power Generation Costs 2019 [19]; IRENA Cost and Competitive Indicators – Rooftop Solar PV 2017 [20] and IEA Monthly Oil Price Statistics 2020 [21].

Data used in VMA were not projections and have been published between 2015 and 2020 and are mostly European specific but sometimes are mingled with global values then detailed regionally explicit data is scarce or not available. Each data-class was added to a table of its own and if relative to conventional technologies, it was submitted to a where a weighting in order to represent the actual mix of these technologies. Then, for each data type, average value is calculated along with one standard deviations margin, calibrated higher and lower values, and eliminating outliers. These average, low and high values can be selected to be used as inputs to the model.

Additionally, other important works not listed in Table 1 that should be mentioned are Equinor Energy Perspectives 2018 [22] and 2019 [23] with its 3 scenarios that explicit the importance of international political collaboration; The European Climate Foundation [24] that among its 4 scenarios, includes the "Demand-Focus" one where there is so much focus on energy efficiency that European TAM in 2050 has followed a declining trend and is supported by a very helpful web database, as well as IRENA Global Energy Transformation 2018 [25] and 2019 [26]; ECOFYS Energy Transition Within 1,5ºC 2018 [27]; BP Energy Outlook 2019 [28]; WEC World Energy Scenarios 2019 [29], [30] and two more JRC reports, the 2018 Global Energy and Climate Outlook [31] and the 2020 Towards Net Zero Emissions in the EU Energy System in 2050 [12].

Table 1: Publications that provided usable scenario projections for Adoption of Solar Technologies, their respective scenarios, issuing body and year of publication.

Source Document Name	Organization	Scenario Name
World Energy Outlook (WEO) 2019 [6]	International Energy Agency (IEA)	IEA Stated Policies Scenario (EU)
		IEA Current Policies Scenario (EU)
		IEA Sustainable Development Scenario (EU)
IEEJ Outlook 2019 [32]	The Institute of Energy Economics of Japan	IEEJ Reference Scenario (EU)
		IEEJ Advanced Technologies (EU)
Energy Tech. Perspectives (ETP) 2017 [33]	International Energy Agency (IEA)	IEA Reference Technology Scenario (EU)
		IEA 2°C Scenario (EU)
		IEA Beyond 2°C Scenario (EU)
Shell Sky Scenario 2018 [34]	Shell	Shell Sky Scenario (Europe)
Decarbonization Pathways Full Study Results 2018 [35]	Eurelectric	Eurelectric Scenario 1 80% Decarbonization (EU)
		Eurelectric Scenario 2 90% Decarbonization (EU)
		Eurelectric Scenario 3 95% Decarbonization (EU)
Net Zero by 2050 From Whether to How 2018 [24]	European Climate Foundation (ECF)	ECF EUREF 16 (EU)
		ECF Shared Effort (EU)
		ECF Demand-Focus (EU)
		ECF Technology (EU)
Deployment Scenarios for Low Carbon Technologies 2018 [11]	EU Joint Research Centre (EU JRC)	JRC Baseline Scenario (EU 31)
		JRC Diversified Scenario (EU 31)
		JRC ProRES Scenario (EU 31)
		JRC ProRES Near Zero Scenario (EU 31)
Decarbonization Pathways 2020 [16]	Guidehouse/Navigant	Navigant Current EU Trends Pathway
		Navigant Accelerated Decarbonization Pathway (EU)
		Navigant Global Climate Action Pathway (EU)
Vision Scenarios for European Union 2017 Update [36]	Oeko Institute	Oeko Reference Scenario (EU 28)
		Oeko Vision Scenario (EU 28)
Global Renewables Outlook (GRO) 2020 [37]	International Renewable Energy Agency (IRENA)	IRENA Planned Energy Scenario (EU) Adjusted
		IRENA Transforming Energy Scenario (EU) Adjusted
Achieving Paris Agreement Goals 2019 [8]	Sven Teske *	Sven Teske 5°C Scenario ("EU")
		Sven Teske 2°C Scenario ("EU")
		Sven Teske 1.5°C Scenario ("EU")
Energy Revolution 2015 [7]	Greenpeace *	GP Energy Revolution ("EU")
		GP Reference ("EU")
		GP Advanced energy Revolution ("EU")
Full Study Energy Transition Europe 2018 [9]	LUT University & Energy Watch Group (EWG) *	LUT & EWG 100% Renewable Energy ("EU")
100% Renewable Europe 2020 [10]	Solar Power Europe (SPE) & LUT University *	SPE & LUT Laggard ("EU")
		SPE & LUT Moderate ("EU")
		SPE & LUT Leadership ("EU")

4. Methodology

Project Drawdown Reduction and Replacement Solutions (RRS) core model, is characterized by its bottom-up design, structured in an Excel workbook where all individual data and calculations are made locally in one file [38]. Model's main inputs are TAM and ADPT projections, and data on various key assumptions such as "First Cost per Implementation Unit", "First Cost Learning Rate", "Lifetime Capacity", "Average Annual Use", "Fixed Operating and Maintenance Cost" (FOM), "Variable Operating and Maintenance Cost" (VOM) and "Indirect Emissions", collectively called Variable Meta-Analysis (VMA) data. There are specific sheets for registering data that will receive statistical treatment for defining mean, high and low values, to make data interpolation, and to organize different TAM and Adoption scenarios in tiers according to their ambition levels.

To determine the impact potential of each solution requires a forecast of implementation based on estimated global functional demand for the period of study (2020-2050). Due to the diverse nature of the many solutions, each one of them will have its own Functional Unit of Measure in order to quantify the impacts of the solution, better expressing the outcome produced. Moreover, it is also necessary to select a specific Implementation Unit of Measure that will quantify the expansion in the adoption of such technology, measuring the pace of "acquisitions" or "installations" of such solution. The two units are closely related: the implementation unit produces the function that is in demand. Considering the case for electricity generation of solar technologies, the Implementation Unit of Measure will be TWp of installed capacity while the Functional Unit of Measure is annual TWh of electricity generated by them [38].

The model presents as results key climate, financial and electricity generation outcomes such as Adoption Estimates, Total Emissions Reduction ($GtCO_{2e}$), Net First (implementation) Cost, Lifetime Operating Cost/Savings [38].

After analysing these reports, an excel sheet was used to curate the content, clearly assigning what type of information was present in which document, and the values obtained for each scenario projection for TAM and for future adoption of the three solar technologies.

Before collecting projections about an uncertain future, one must create a solid base about the past. At this phase, the goal was to create a historic time-series for the solar power technologies from 2000 until the most recent data available which, at that time, was 2017. Considering that IRENA keeps a more detailed and, perhaps, more accurate backtrack of Renewable Energy outputs its database, the IRENA downloadable dataset [39], was chosen for renewable sources, complemented by IEA's historical data, freshly published in European Union Energy Policy Review [40] , was used for non-renewable electricity i.e., nuclear and fossil fuel powered (coal, oil, gas) power plants.

In order to become useful in this part of the work, reports must provide Total Addressable Market (TAM) or Adoption (ADPT) projections. In total, 37 TAM projections have been collected along with 16 adoption projections for each solar technology.

Originally only the Shell Sky [34] and LUT & EWG Full Study Energy Transition Europe [9] publications have separate projections for U-PV and D-PV. Most reports only offer a generic "Solar PV" label, sometimes mentioning that this group encompasses both centralized and decentralized variants, but in general there is not much attention to disaggregating one from another. And it is quite understandable after all they share the same technology and only for very specific purposes it would be useful to separate them. The overall scarcity of native D-PV data motivated the adaptation of data that originally was referred as "Solar PV" to be split into two parts, D-PV and U-PV. The average present (2020) ratio between D-PV and U-PV from the publications that originally have projections for both classes have been used for defining the ratio to be applied in other projections homogeneously for every year. It may be a rough assumption to guess that these ratios will remain unchanged, but it would take a stronger reason to do it otherwise. Thus, in the absence of any compelling indicator of change, the ratios were kept stable for the future. The resulting ratios were 61% and 39% for U-PV and D-PV, respectively. For the sake of comparison, Project Drawdown 2020 review has adopted rations of 60% and 40% [41][42].

Currently designed in excel, the model limits the total amount of TAM scenarios to be used up to 15. This quantity is then divided in 4 tiers: Modest, Intermediate, Ambitious and Extremely Ambitious. For each one of these tiers, an average projection is created that will be used together with ADPT projections. The same tier classification is done for ADPT projections. The average ADPT projection of each tier has also received a specific run of the model, coupled with the respective TAM.

Each run of the model consists of a selection of a specific TAM and ADP projection including values for VMA data. Then the performance of each scenario is measured against a Reference Adoption Scenario where the solution share is fixed in time to its current ratio, and the analysis is conducted comparing the projected solution adoption versus continued used of conventional technologies.

5. Results and Discussion

Table 2 shows the results of the Variable Meta-Analysis executed in this work for economic, technical, and environmental parameters, whose mean values were used as inputs to run the model. Although all economic inputs were converted to US$2014 in order to become inputs to the model, here they are shown in euros of 2019 in order to maintain homogeneity with economic results that will be later exposed. The original work that supports this extended abstract has individual VMA results for each one of the solar technologies as well as for conventional technologies solar solutions replace.

The most condensed way of displaying another core result of this work is portrayed in Figure 1. It consists of the range of projected scenarios results, including outliers, for environmental, economic and generation types of results. All spectrum of scenarios is used to compose the range for each technology. Placed side to side is possible to compare how solar technologies perform against each other. One clear takeaway is the prevalence of U-PV especially in generation and avoided emissions. Individual results from six scenarios project U-PV generation to be over 1,000 TWh in 2050 while for D-PV there are 4 scenarios, and for CSP only one. It is interesting to notice that most of the energy sector expects not only the growth of solar-powered technologies for energy generation but also a dominance of PV technology at utility scale.

It becomes clear that in most projections Utility Scale PV is bound to be the most relevant of Solar Technologies for electricity generation in the future, maybe even, the single most relevant technology for electricity generation due to its elevated attained share in some scenarios. Results from this work indicate that U-PV will represent from 3.92% to 20.86% of the European power sector mix in 2050. The most optimistic scenario suggests a staggering 39% share.

To realize how projections for U-PV are bold it is interesting to compare it against current total generation numbers in Europe. According to the many sources consulted in this work, in 2017, 3250 TWh of electricity has been generated in Europe while the average projected generation for U-PV in 2050 is around 1380 TWh, just shy of half the current generation, only from U-PV. Furthermore, this also puts in perspective the magnitude of the outlying results that projects around twice as much generation from U-PV than current total energy generation mix.

For the sake of comparison, projections realized in this work point to D-PV representing 2,5% to 8,6% from the European the electricity generation mix in 2050, and CSP, 0,9% to 7,6%.

In Figure 2 one can observe the combined generation from the three solar technologies and how each one of them contribute to the total solar generation, both in 2020 as in 2050. It shows the sum of results for each solar solution for aggregated by tier and the great difference they imply, hence the huge variation in the range of results yielded in this study. Additionally, it corroborates the great optimism in U-PV growth, especially, since the average ambitious scenario projects more than 2000 TWh of generation from that source in 2050.

Another important point to observe is that CSP technological solution is regarded with more scepticism by most publications. This could be a direct consequence of the fact that CSP is as matured of a technology as their photovoltaic counterparts. However, unsatisfactory economic results, such as seen in the previous section for Lifetime Operating Savings, can be a true warning sign for the future development of this technology branch that is still lagging behind. The cumulative installation costs for CSP are noticeably smaller as

Table 2: Variable-Meta Analysis for Utility Scale PV

UTILITY-SCALE SOLAR PHOTOVOLTAICS (U-PV)					
VMA Parameter	**Unit**	**Datapoints**	**Mean Value**	**High Value**	**Low Value**
First Cost per Implementation Unit	€2019/kWp	53	1 376	1 882	870
First Cost Learning Rate	%	3	18%	25%	11%
Lifetime Capacity	hours	9	34 986	38 266	31 706
Average Annual Use	hours/a	29	1 312	1 650	974
Variable Operating Cost (VOM)	€2019/kWh	7	0	0	0
Fixed Operating Cost (FOM)	€2019/kWp	16	16,94	21,34	12,54
Indirect GHG Emissions	tCO2e/TWh	11	48 450	78 557	18 345

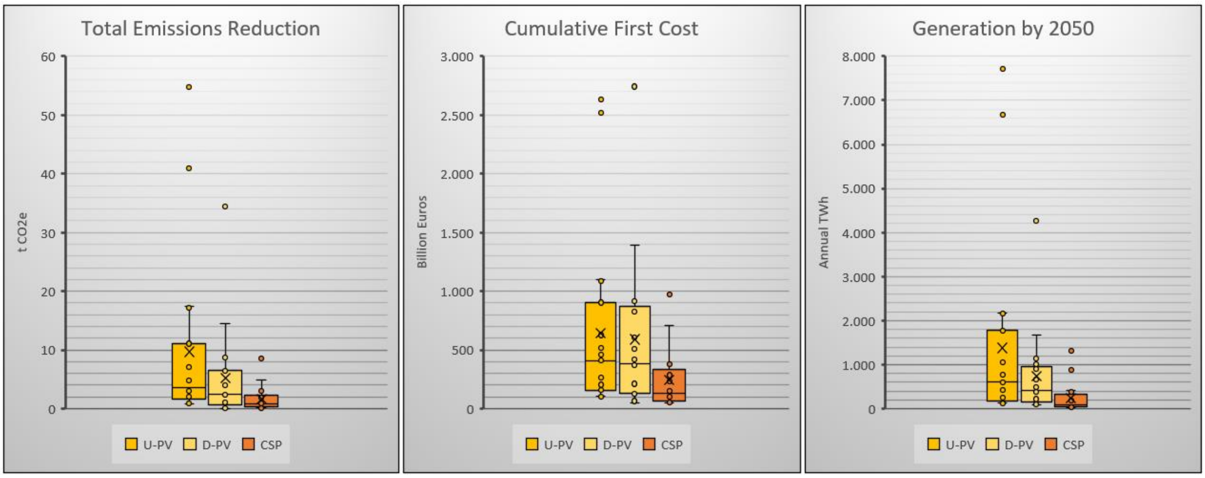

Figure 1:Three types of results represented by Total Emissions Reduction (Environmental Result), Cumulative First Cost (Economic Result) and Electricity Generation by 2050 (Generation Result).

a result of much smaller adoption despite its much higher cost per unit of measure (€/kWp).

Of course, no projection accounted for the huge disarray caused by COVID-19 pandemic. Many publications issued during 2020 pointed at the decline in electricity consumption delaying new energy investment [43][44]. Renewable energy is not immune to the crisis brought by the global pandemic but they are more resilient [4]. This is due to the increased volatility in prices caused by this global disruption. Fuel prices are the most impacted part of energy sector, oil and coal especially [45].

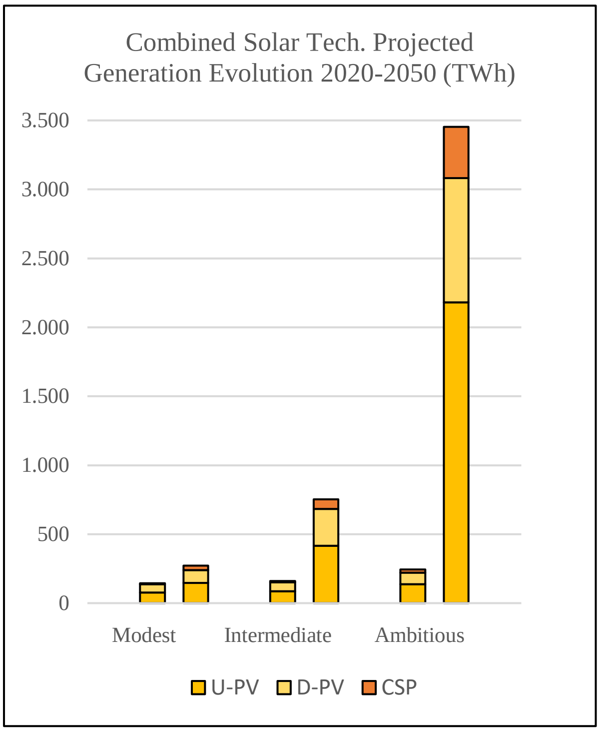

Figure 2: Differences of projections among different Tiers for electricity generation of solar technologies and their evolution in time. Left bars for 2020 and right bars for 2050

6. Conclusions

Results from this study point to a significant increase in solar-based power generation, especially for PV class, but also for CSP when compared to present values, but they are unable to give a specific number for how much U-PV, D-PV or CSP generation there will be in 2050. The sources that supported this work were not predictions nor bets, but rather projections based on the various possibilities of technological availability and development, climate mitigation ambition and political choices that lie ahead of us. But there will be no single technology, not even a single sector that by itself could solve all intricate challenges of Energy Transition or Climate Change. Some, like the Power Sector, are strategic in the sense of the many integrations and cross-industry repercussions it can unlock. Doubling down the intrinsic transversality of the power sector seems to be an obvious bet because it can decarbonize virtually any other sector that consumes energy if that energy is carbon neutral.

There is still some room for improvement in this work, of course. Direct substitution of traditional and dispatchable forms of generating electricity for VREs is a hard assumption with many hidden costs that have not been considered in this work. Comparing CSP that includes certain degree of dispatchability and storage, to other solutions such as PV that do not, may have been a good first approach. But, perhaps, future works similar to this one should consider an association of PV and batteries (or any given storage solution), at least at the Utility scale level, for levelling the comparison with CSP. It is important to highlight that energy storage along with dispatchability cannot be perceived merely as a desirable feature for power generation solutions since it is already a built-in feature for the pollution fossil fuel fired power plants.

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