User guidelines for "MyPV-LCOE" tool

(PV design support tool)

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Abstract	The present document serves as a complement to the software tool "MyPV-LCOE", created to assist various types of users in designing and evaluating PV systems. The tool was developed within the framework of WP1 of the SESA project and is available through its toolbox package. Conceived as "user guidelines", this document provides a description of the tool and simplifies its usage. It consists of three main chapters, covering context, tool description and user guidance and some references for further information.

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List of Abbreviations

BoS	Balance-of-System		OPEX	Operational expenditure
CAPEX	Capital expenditure		PR	Performance Ratio
CDS	Climate Data Store		PV	Photovoltaic
EU	European Union		RCM	Regional Circulation Model
GCM	General Circulation Model		RCP	Representative Concentration Pathway
GHG	Greenhouse gases		SSP	Shared Socioeconomic Pathway
GWL	Global Warming Level		SW	Software
IPCC	Intergovernmental Panel on Climate Change		WACC	Weighted Average Cost of Capital
KPI	Key Performance Indicator		WG	Working Group
LCOE	Levelized Cost of Energy		WP	Work Package
O&M	Operation and Maintenance		yr.	year

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Introduction

SESA (Smart Energy Solutions for Africa) is a collaborative project between the European Union and nine African countries (Kenya, Ghana, South Africa, Malawi, Morocco, Namibia, Tanzania, Rwanda, and Nigeria) that aims at providing energy access technologies and business models that are easily replicable and generate local opportunities for economic development and social cohesion in Africa. Through several local living labs, the project will facilitate the co-development of scalable and replicable energy access innovations, to be tested, validated, and later replicated throughout the African continent. These solutions will include decentralised renewables (solar photovoltaics), innovative energy storage systems including the use of second-life electric vehicle batteries, smart microgrids, waste-to-energy systems (biomass to biogas), climate-proofing, resilience and adaptation, and rural internet access.

In this context, and within the framework of Work Package (WP) 1, a software (SW) tool has been developed oriented to assist photovoltaic (PV) project promoters, PV system planners/designers, researchers, and public authorities (such as municipalities) in the design and evaluation of PV systems. The utilization of the tool will serve various purposes depending on the type of user. For some, it will help in investment and design decision making (optimal location for a PV installation, best PV technology, PV system layout, etc.); for others, it will facilitate evaluating the impact resulting from specific research-based improvements; and, other users (like municipalities and public bodies), can use it to support informed political and environmental decisions.

To facilitate its use withing the project, this SW tool is included as part of the SESA toolbox package throughout the entire duration of the SESA project, running on a server. Apart from the tool itself, the present document is annexed to it. This document was conceived as “user guidelines” describing the tool and making its use easier.

This document is composed of three main chapters:

- Context: this section provides a description of the primary reasons behind the development of the tool, along with the key theoretical concepts that have been implemented.
- Tool Description and User Guidance: in this chapter, the tool is described, including information about its different modules and step-by-step instructions for using it.
- References: this section summarizes the most relevant references that can be consulted for further information

1. Context

The tool described in these guidelines aims to assist and streamline PV systems design and investment, evaluate the impact of innovations, and assess how climate change could affect future financial and energy conditions of this type of installations.

Electricity is the fastest-growing source of final energy demand and, over the next 25 years, it is expected to outpace overall energy demand growth. A faster rise rate is expected for global electricity demand over the next two years, reaching an average of 3.4% annually through 2026. In this context, renewables contribution to global electricity production is expected to rise, accounting for the 37% in 2026. And the main driver of this growth would be the expansion of ever cheaper PV technology [2].

The proposed tool is designed to be used by a diverse audience, including PV project promoters, systems planners/designers, researchers, and public authorities (such as municipalities). Different needs are covered, being helpful not only in the investment decision making (by providing essential information on best location for the installation, best PV technology, PV system layout, etc.), but also in research (by allowing the evaluation of the effect that certain improvements can have on the feasibility and profitability of the installation), and the informed adoption of political and environmental decisions by public bodies (by providing valuable information about potential effects of climate change on future renewable energy generation, for example).

For doing so, the tool encompasses Levelized Cost of Energy (LCOE) estimation. The LCOE value is considered as one of the most important KPIs (Key Performance Indicator) to measure the profitability and successful design and planning of a PV installation [4] and it's very useful to analyse the impact of one (or several simultaneous) change in some of the parameters (costs, efficiencies, extension of lifetime, change in radiation or temperature conditions...). At research level, it is commonly used to evaluate the impact of a specific innovation introduced in any of the elements/components of the PV system.

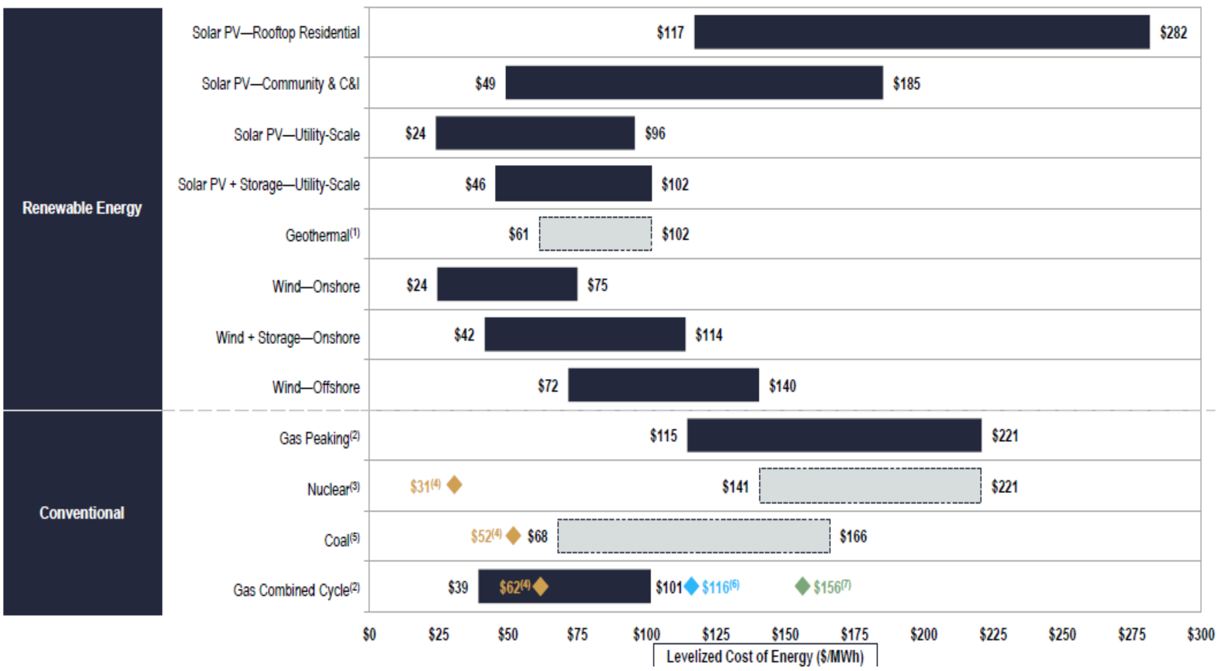


Figure 1.1 Levelized Cost of Energy Comparison for different energy generation technologies[5]

LCOE assessment is well known in the PV sector, though its evaluation is usually assessed by means of an excel file, very limited in fields and rigid in the way of interacting. This tool, however, allows the user to feed the model with multiple fields, under the appearance of a software application.

Another novelty of this tool is the inclusion of climate change evolution in the decision, which is unique, not expected in the market. The common practice in PV industry is to design based on historical climatic conditions (weather databases), without taking into account changes that could occur in the future. Obtained design/investment decision could not be fully adapted to future conditions, leading to malfunctioning, a reduction in efficiency, lifetime or, in the case of an investment, poorer RoI (Return-of-Investment).

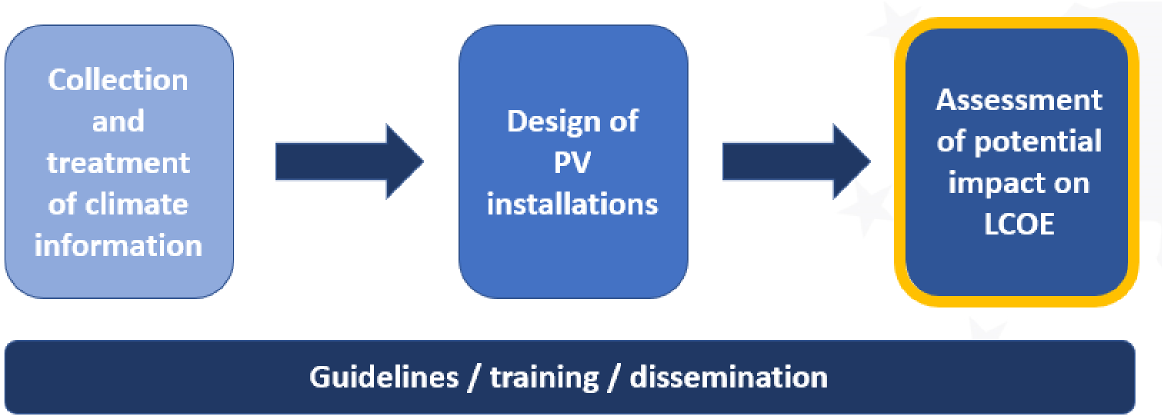


Figure 1.2 Scheme representing design of PV systems process, including the analysis of climate change

All these functionalities are particularly suitable to complement decision making process in ground large scale PV systems (> 10 MW), which are expected to represent about the half of future PV systems.

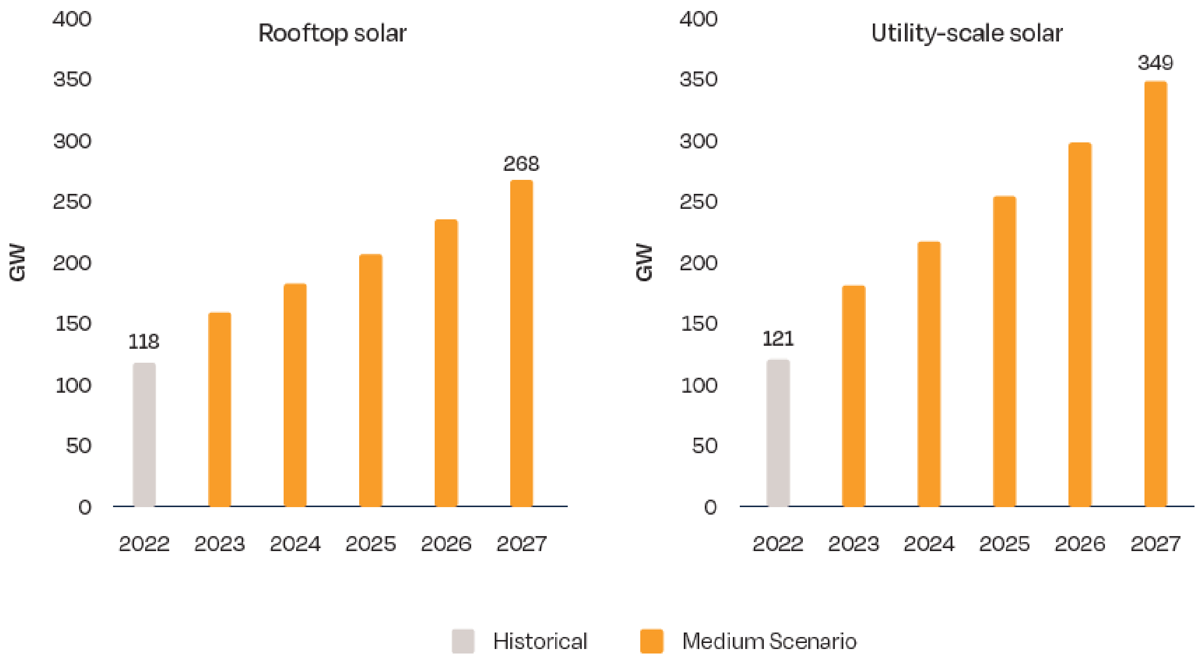


Figure 1.3 Solar PV rooftop and utility-scale segments scenarios 2023-2027 [6]]

1.1. Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy/Electricity (known as LCOE) provides valuable insights for investors and policymakers, guiding decisions on energy infrastructure and sustainability. A financial definition of LCOE states that it is the price at which the generated electricity should be sold for the system to break even at the end of its lifetime [51]. It can be calculated using the following equation [7].

LCOE is a key parameter used in investment planning to assess the feasibility and profitability of energy projects, allowing fair comparison across generation technologies (renewable and/or conventional) with different sizes, life spans, risks and capacities.

It represents the average net present cost of energy generation (usually electricity) for a specific system over its entire lifetime. Typically measured in currency per energy unit (such as €/kWh or USD/kWh), it encompasses all the costs (including initial investment, operation and maintenance, fuel expenses, and the cost of capital) and profit margins.

The LCOE is calculated by dividing the discounted sum of all costs to build and operate a power-generating asset by the discounted sum of actual energy generated thus costs divided by energy production in its lifetime.

$$LCOE = \frac{Total\ cost\ for\ the\ whole\ plant\ lifetime}{Total\ energy\ production\ for\ the\ whole\ plant\ lifetime}$$

Average total cost estimation combines capital expenditure (CAPEX, initial costs including financing) and operational expenditure (OPEX, annual operational expenses). In particular, for PV plants:

- All-inclusive turnkey PV system price to be paid upfront is included in CAPEX, being fully paid during the year of installation. The main component costs are: modules, inverter units, trackers/structures, rest of Balance-of-System (BoS) elements[1] and cost of installation[2].
- In OPEX, ongoing costs associated with operating and maintaining the plant are usually considered: routine maintenance, cleaning, monitoring, etc. For PV plants, as no fuel cost related to generation exists, this will not be included. It is typically expressed as an annual value in €/MWh or €/MWp and can include fixed costs (preventive and predictive O&M) and variable costs (corrective O&M, once the failure has occurred). Asset management, insurance, security, network access fee, billing and monitoring are also considered in this component.
- Other cost to be included is land acquisition (in case of ground-mounted plants), accounted as an annual rental (OPEX) or upfront investment (CAPEX) if purchased.
- Cost to decommission the PV power plant at the end of lifetime (disposition costs), including direct (labour, equipment) and indirect cost of PV plant de-installation, demolition, recovery, and land reclamation; module recycling cost; landfill disposal cost (including landfill tipping fees and hauling, of non-salvageable material); income from scrap of steel, copper and aluminium recovered and sold to recyclers and from reclaimed land.

[1] Within the Balance-of-System (BoS), there are items efficiency-related (cabling, structures, transport…) and non-efficiency related (combiner box, transformers, fuses, protections, monitoring tools, etc.).

[2] Administrative costs (e.g. permissions, local taxes, documentation), cost for planning, engineering and project management, cost of PV plant construction (mounting, cabling, installation) and development, installer's margin, etc.

With regard to energy production, it is dependent on plant extension, local irradiation (kWh/m2.year), Performance Ratio (PR)[3], degradation (%) and lifetime (years).

Both O&M costs and energy production are highly dependent on climate conditions and, in consequence, on climate change. The terms of this dependency are explained in the next chapter (0).

GENERAL/SIMPLIFIED EXPRESSION

$$LCOE = \frac{Total\ cost\ for\ the\ whole\ PV\ plantlifetime}{Total\ energy\ production\ for\ the\ whole\ PV\ plantlifetime}$$

- $$LCOE = \frac{CAPEX + OPEX\ (PV)}{EP\ (PV)}$$

  CAPEX: Capital Expenditure
  OPEX: Operational Expenditure
  EP: Energy/Electricity Production
  PV: Present value

Detailed EXPRESSION

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX\ (t)}{(1 + WACC_{Nom})^t}}{\sum_{t=1}^{n} Yield(0) * \frac{(1 - Degr)^t}{(1 + WACC_{Real})^t}}$$

t is year number ranging from 1 to the economic lifetime of the system
CAPEX is total investment expenditure of the system, made at ***t*** = 0 in €/kWp
OPEX(t) is operation and maintenance expenditure in year ***t*** in €/kWp
Yield(0) is initial annual yield in year 0 in kWh/kWp without degradation
Degr is annual degradation of the nominal power of the system
$WACC_{nom}$ is nominal weighted average cost of capital per annum
$WACC_{real}$ is real weighted average cost of capital per annum

Figure 1.4 Calculation of LCOE (Simplified and detailed expression)

According to the Annual Technology Baseline, edited by NREL [8], the following cost items are included in CAPEX and OPEX for all technologies (including PV).

Table 1.1 Summary of concepts by category within the CAPEX

Category	Item
Balance of system/balance of plant	All other major plant components within the facility fence line necessary to deliver electricity to the bulk power system.
Electrical infrastructure & interconnection (electrical interconnection, electronic, electrical infrastructure**)**	Internal and control connections Onsite electrical equipment (e.g., switchyard) Power electronics Transmission substation upgrades
Generation equipment & infrastructure (civil works, generation equipment, other equipment, support structure)	Plant construction Power plant equipment
Installation and indirect costs	Distributable labour and materials Engineering Start-up and commissioning
Owners' costs	Development costs Environmental studies and permitting Insurance Legal fees Preliminary feasibility and engineering studies Property taxes during construction
Site costs	Access roads Buildings for operation and maintenance Fencing Land acquisition, site preparation Transformers Underground utilities

[3] PR is defined as ratio between electricity actually generated by the PV system and the electricity that an ideal lossless PV system would produce with the same amount of irradiation and 25ºC cell temperature. Losses can be caused by high ambient temperature, dust and dirt, mismatching, DC to AC losses in inverter, inverter saturation, transformer losses, etc.

Table 1.2 Summary of concepts by category within the OPEX [8]

Category	Item
Fixed costs	Administrative fees Administrative labour Insurance Land lease payments Legal fees Operating labour Other Property taxes Site security Taxes
Fixed costs components	Project management
Maintenance costs	General maintenance Scheduled maintenance over technical life Unscheduled maintenance over technical life
Variable cost components	Consumables (e.g., water, chemicals, catalysts, etc.) Waste disposal (e.g., ash, slag, process wastes, process byproducts that are not otherwise sold, etc.)
Maintenance components	Transformers
Replacement costs	Annualized present value of large component replacement over technical life

1.2. Climate Proofing of PV projects

Climate change is already affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes [9]. Despite the clear commitment from the EU and the international community to reduce emissions, climate change remains inevitable and proposed solutions will have to operate under a changing climate. Throughout their entire lifetime, they will both "be impacted by" and "impact" the environment in various feedback loops. However, this perspective was not traditionally addressed, considering stationary climate perspective in the analyses instead, which limited long-term resilience.

Climate proofing seeks including this approach. The objective is to ensure that climate-related risks and opportunities are integrated into the design, operation and management of any kind of project, improving its behaviour, for the whole lifetime, under changing climatic conditions [10]. In this context, ensuring future performance entails evaluating the functionality in relation to projected climatic conditions.

With regard to PV systems, they are sensitive to climate change, being changes in solar irradiation the most obvious climate hazard. However, other variables can also affect these plants and, even though they are usually mentioned, they are seldom quantified, which may lead to an underestimation of their importance [11].

In general, potential impacts could be grouped in two types, affecting the power output or lifetime of the PV system:

- Power output could be mainly affected by changes in solar irradiation, which is linked to the number of sunny hours (cloud coverage), air turbidity (dust, humidity, atmospheric particles) or cleanliness of the panel (dust, sand, precipitation, snow, wind). These are difficult to predict, being very location-specific and extremely complex systems. Another well-known factor is the PV panel temperature, that affects the efficiency of the cells, linked to changes in mean temperature and wind.
- Physical integrity of the infrastructure (modules, batteries, etc.) could suffer faster aging and degradation or be damaged by extreme weather events (like wind gusts, storms, hailstones, flooding, landslides, fires, etc.).

They are summarized in Table 1.3.

Table 1.3 Summary of climate hazards potentially affecting solar infrastructure projects and type of impact (based on [16])

Exposed component	**Climate hazard**				
	Solar irradiation	Ambient temperature	Wind speed	Humidity	Extreme weather events
PV cell	Impact on cell temperature and efficiency	Impact on cell temperature and efficiency	Impact on cell temperature and efficiency	Oxidation, corrosion and efficiency	
PV installation	Impact on power output.	Impact on power output.	Impact on power output.	Impact on degradation pace and power output.	Impact on lifetime.
Service	Service affected	Service affected	Service affected	Service affected	Service affected

* Cells colours reflect the relevance and frequency of the expected impact (the darker the higher)

While numerous studies have explored the effects of climate change on PV potential, there remains a lack of understanding regarding how these impacts specifically influence its economic viability. LCOE (**¡Error! No se encuentra el origen de la referencia.**) allows its quantification in the “design stage” by evaluating its behaviour throughout the entire lifetime of the installation under current climate and climate change scenarios. This provides useful information to designers that can adjust certain parameters to make their projects viable and/or more profitable.

When evaluating capital expenditure (CAPEX), certain costs directly hinge on factors like location and environmental and socioeconomic factors (such as climate, orography, distance to essential infrastructure, land use and price, etc.). The impact of climate change will primarily manifest in the longevity of infrastructures as a consequence of gradual aging and degradation, which can be complex to precisely quantify. Dependent on factors such as cell type, energy production and local climate, it may have its origin in chemical and material processes linked to outdoors exposure, oxidation, corrosion and thermal stress, all of them highly influenced by climate change. Additionally, extreme events (such as hailstorms or high winds) can exert mechanical loads, potentially reducing lifespan of the installation. Nevertheless, suitable design of the infrastructure and encapsulation of modules increase its resilience to these hazards, improving robustness in case of exposure to humidity, oxidation and extreme conditions. Given the complexity linked to these considerations, CAPEX calculations often incorporate site-specific and constant terms for the whole lifetime of the installation.

In relation to operational expenditure (OPEX), it could be increased due to extreme events that generate mechanical stress and alter the frequency of cleaning requirements. Similar to CAPEX, it is common practice to consider constant, site-specific values, overlooking the impact of climate change. Nevertheless, when data are available, it is advisable to evaluate climate-driven potential changes and verify the suitability of this approximation.

When considering energy generation, ambient conditions can significantly impact this term, in particular, radiation and ambient temperature. For these two variables, climate models offer good quality data, with moderate uncertainties, facilitating their evaluation under climate change scenarios, throughout the entire lifetime of the installation.

Table 1.4 Main climatic hazards and their potential consequences on PV installations (based on [16])

Climate hazard	Potential Impact	Consequence
Changes in solar irradiation	Direct impact on power output.	Consequences for the economic performance of the installation and the service given.
Changes in ambient temperature	Direct impact on PV cells and other components efficiency and therefore the power output.	Consequences for the economic performance of the installation and the service given.
Changes in wind speed (average)	Direct impact on PV cells efficiency (cooling) and therefore the power output.	Consequences for the economic performance of the installation and the service given.
Extreme weather events	Direct impact on mechanical load to be supported by the infrastructure.	Consequences for physical integrity of the infrastructure (lifetime) and economic performance of the installation. Potential consequences for the service in case of damages.

In this context, developed tool considers projected changes in ambient temperature and radiation to quantifying their potential impact on LCOE under current climate and climate change scenarios (see Table 1.6).

1.3. Main concepts in climate change analysis

As already mentioned, the proposed tool aims to integrate a non-stationary conception of the climate into the design of the PV projects, understanding that climate conditions are being modified by the effect of climate change [16] mainly boosted by increasing anthropogenic emissions of greenhouse gases (GHG).

1.3.1.Climate and climate change

The term *"climate"* is used to describe the characteristics of the atmosphere as a stationary system, assuming that the average value of these properties tends toward a specific and stable value over the long term. Typically, climate characterization is conducted over 20 or 30-year periods, which is considered short enough time span to meet the stationarity hypothesis, yet long enough to define representative statistics for the period. It is important to note that while the stationarity hypothesis holds for periods of 20 - 30 years, "*climate change"* will alter future climate statistics. This results in a transition from an initial stationary state (characterized by certain variable values) to a final stationary state (characterized by different variable values) where changes occur slowly enough that non-stationarity effects are not noticeable beyond the change in representative parameters [16].

The term climate change encompasses all the alterations that the statistical properties of the climate will undergo in the long term due to various factors. Those changes affect both the values of the variables and their spatial and temporal patterns. This implies that a general increase in global temperature does not uniformly result in the same value change across all locations on the globe, but rather it leads to a spatial distribution influenced by various factors. These changes do not necessarily have to generate negative changes or induce impacts. Climate change will also lead to the appearance of changes that could be positive, i. e. increasing average rainfall in places of scarcity, decreasing the occurrence of floods in some areas, etc. [16]

Within the mentioned 20 or 30-year periods, the characterization of climate variables can be carried out at different scales depending on the availability of information and the level of detail required in the representation of the studied phenomena. The daily scale represents a scale of commitment, and, in some cases, it can even extend to an hourly scale [16].

1.3.2. Models

To determine how the climate might change in future, complex "*models"* are built that rely on regionally differentiated simplifications and assumptions about forthcoming socioeconomic and technological settings related to climate. These models solve the dynamic and thermodynamic equations of the atmosphere, and those of its interaction with other terrestrial systems such as seas and oceans, and frozen bodies. The atmospheric properties for the entire globe are resolved by the *General Circulation Models (GCM)*. They offer low spatial resolution, which is improved by *Regional Circulation Models (RCM)* that take the atmospheric conditions resolved by the GCM to use them as boundary conditions and solve the equations of atmospheric dynamics on meshes of higher spatial resolution (around 25 km on a side), covering smaller geographical areas than those of the GCM [16].

There are numerous climate models from different institutions, each with its strengths and weaknesses. Due to this, climate change analyses must consider several climate models in order to reduce the uncertainty about climate change projections. The selection of models should be based on the quality of their representation of the specific variables relevant to each study and try to obtain the widest variety of climate projections [16].

Developed tool provides a method to guide and simplify the selection of preferred models for LCOE assessment of PV projects (see chapter 2.2).

1.3.3. Climate scenarios

The definition of the scope of the study is one of the main points for climate risk analyses in any sector. Due to the uncertainty in the future behaviour of the climate, the analysis of the future effects of climate change has to be based on scenarios. Each climate model generates sets of projections, known as *"climate scenarios" or "pathways"*[4], which offer not predictions or forecasts but different plausible climatic futures for the various climatic variables. These futures depend on how the society address climate change (*"climate resilient development"*[5], see Figure 1.5). By exploring multiple possible events, these scenarios help address uncertainties stemming from societal forces, policy decisions, alternative future emission trajectories, emission conversion, natural variability, modelling limitations, etc. [19].

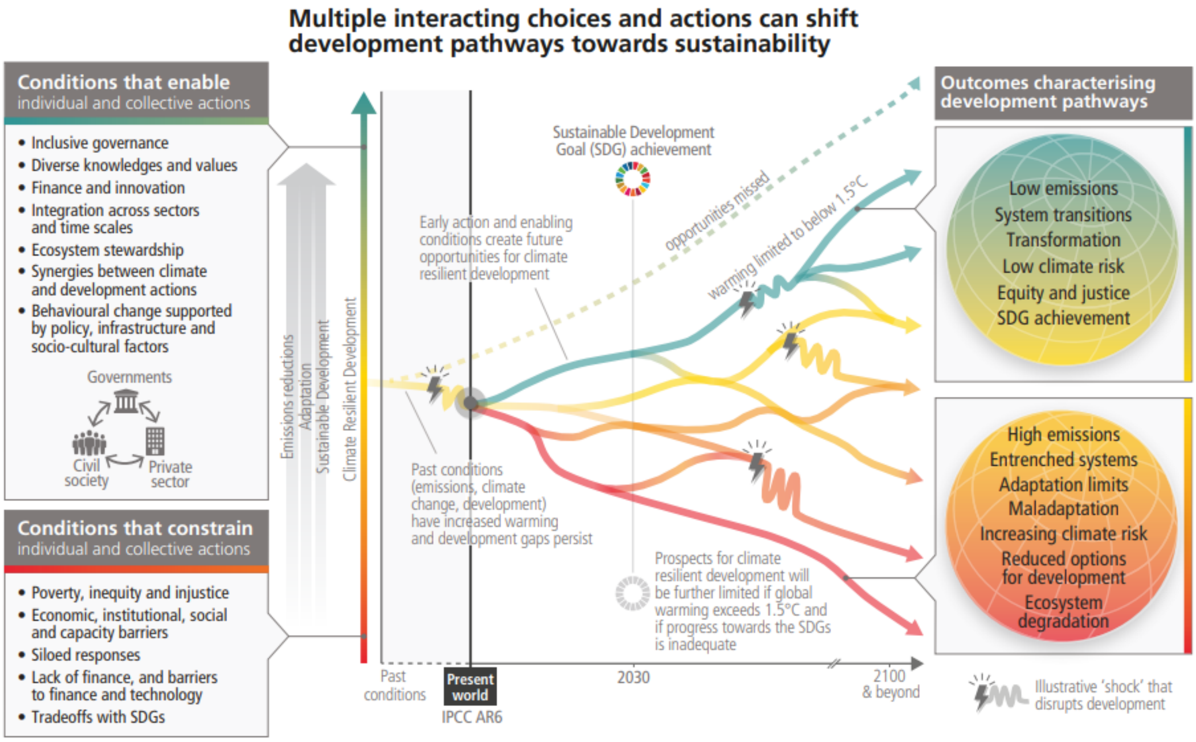


Figure 1.5 Climate resilient development: illustrative development pathways (red to green)[6], associated outcomes (right panel) and enabling and constraining conditions (left panel) [20]

It is common the use of three plausible situations depending on the considered future warming level: pessimistic (high warming level), optimistic (low warming level) and intermediate or neutral. For defining them, several frameworks are available, including *Global Warming Levels (GWL)*[7],

[4] In the literature, the terms pathways and scenarios are used interchangeably, with the former more frequently used in relation to climate goals

[5] Climate resilient development is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development [20].

[6] Diverging pathways illustrate that interacting choices and actions made by diverse government, private sector and civil society actors can advance climate resilient development, shift pathways towards sustainability, and enable lower emissions and adaptation [20].

[7] The levels of global warming, used in the Paris Climate Agreement at COP21 in 2015, are based on the increase in global average temperature that may occur by the end-of-century with respect to pre-industrial average.

Representative Concentration Pathways (RCP)[8], and *Shared Socioeconomic Pathways (SSP)*[9] (more detailed information in [20]). These approaches are interrelated, showing different levels of GHG mitigation and warming levels (see Figure 1. and Figure 1.7).

Category description	GHG emissions scenarios (SSPx-y*) in WGI & WGII	RCPy** in WGI & WGII
limit warming to 1.5°C (>50%) with no or limited overshoot	Very low (SSP1-1.9)	
return warming to 1.5°C (>50%) after a high overshoot		
limit warming to 2°C (>67%)	Low (SSP1-2.6)	RCP2.6
limit warming to 2°C (>50%)		
limit warming to 2.5°C (>50%)		
limit warming to 3°C (>50%)	Intermediate (SSP2-4.5)	RCP 4.5
limit warming to 4°C (>50%)	High (SSP3-7.0)	
exceed warming of 4°C (>50%)	Very high (SSP5-8.5)	RCP 8.5

Figure 1.6 Description and relationship of scenarios considered across IPCC - AR6 Working Group (WG) reports [20][10]

As previously mentioned, the realization of these pathways depends on the interaction of many socio-economic dynamics and some physical processes that affect the global system that are not yet known in detail. This is why it is not possible to assign a probability of occurrence to each of them, nor assume that they contemplate, or are representative, of the total possibilities. For this reason, a more robust decision-making process will recommend considering several of these pathways (at least two) that allow covering a sufficiently wide range of possible emissions futures that could be faced in the medium and long term [16].

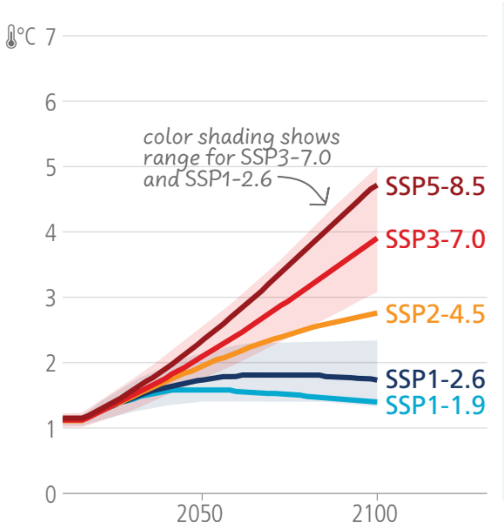


Figure 1.7 Global surface temperature changes across the 21st century relative to 1850-1900 for the five GHG emissions scenarios considered by IPCC-WGI (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) [20]

[8] The Representative Concentration Pathways were developed by the IPCC to describe climate scenarios with different levels of greenhouse gases (GHGs) that may occur in the future.
[9] Shared Socioeconomic Pathways were developed by the IPCC looking beyond GHG emissions and describe futures based on global socio-economic challenges for mitigation and adaptation to climate change, exploring how the global economy and society may evolve over the next 80 years.
[10] (*) The terminology "SSPx-y" is used, where 'SSPx' refers to the Shared Socio-economic Pathway describing the socio-economic trends underlying the scenario, and 'y' refers to the approximate level of radiative forcing (in watts per square metre, or Wm–2) resulting from the scenario in the year 2100. (**) The scenarios "RCPy" are indexed to a similar set of approximate 2100 radiative forcing levels (in W m-2).

All these pathways are described using temporal scenarios covering periods of 20 or 30 years each, where the variables used to characterize the climate can be considered to have a stationary value [16]. When defining the adequate time horizons, it is recommended considering as many periods as needed to cover the whole lifetime of the analysed project (as long as required information is available).

On the other hand, it is important to mention that scenario analysis typically relies on relative values rather than absolute values, offering information on estimated/observed changes in certain scenarios relative to other scenarios. In this sense, a *"baseline scenario"* is usually used for reference, which could be described by historical or present-day conditions and would be considered representative of the reference climate. The values of any variable defined for this period constitute the baseline on which the rest of the changes will be quantified. Future scenarios will then show the change in climate conditions with respect to that baseline.

Summarizing, a typical climate analysis would include at least 5 to 10 scenarios that cover a wide range of possible emissions futures for the whole lifetime of the project and a reference scenario (Table 1.5).

Table 1.5 Example of potential scenarios to be considered in climate analyses

		Reference	Development pathways		
			Pessimistic (high warming level)	**Intermediate or neutral**	**Optimistic** (low warming level)
Historical / present day (20-30 yr.)		**Baseline scenario**	-	-	-
Future scenarios (20-30 yr.)	**Short term**	-	**Scenario 1**	Scenario 2	**Scenario 3**
	Medium term	-	**Scenario 4**	Scenario 5	**Scenario 6**
	Long term	-	Scenario 7	Scenario 8	Scenario 9

* Text in **bold** highlight the most frequently used scenarios

The results obtained (following the process explained in chapter 2) will reveal variations in the LCOE based on the scenario under consideration. This allows for the comparison and adjustment of parameters to minimize its value in the context of future climate change conditions.

Table 1.6 Example of obtained results from "MyPV-LCOE" tool

Reference (without climate change)	Development pathways		
	Pessimistic (high warming level)	**Intermediate or neutral**	**Optimistic** (low warming level)
$LCOE_0$	$LCOE_1$	$LCOE_2$	$LCOE_3$

Chapter 2.2 describes the scenarios specifically considered by this tool.

2. Tool description and user guidance

This SW tool allows selecting the best PV system design based on LCOE estimation, by comparing different technical solutions and locations and taking also into account future climate conditions, optimizing costs, operation conditions and efficiency for the whole lifetime. It also allows sensitivity analyses of LCOE by modifying one or several parameters within a range, and then plotting this information in a graphic or just displaying a table with the most important results.

2.1. LCOE Assessment Module

In order to calculate the LCOE for your PV installation the following steps should be taken:

1. Login / register in the webpage: https://www.mypv-lcoe-prosesa.energy.tecnalia.dev/
2. Create a new project & Introduce the input information:
    a. Energy production
    b. Weather
    c. Financing
    d. CAPEX
    e. OPEX
3. View of outputs:
    a. System Outputs (energy outputs)
    b. CAPEX
    c. OPEX
    d. LCOE
4. Select the operation to be done once PV system is already created:
    a. LCOE Variants
    b. Sensitive Analysis

2.1.1. Login / register in the webpage

Login / register in the webpage: https://www.mypv-lcoe-prosesa.energy.tecnalia.dev/

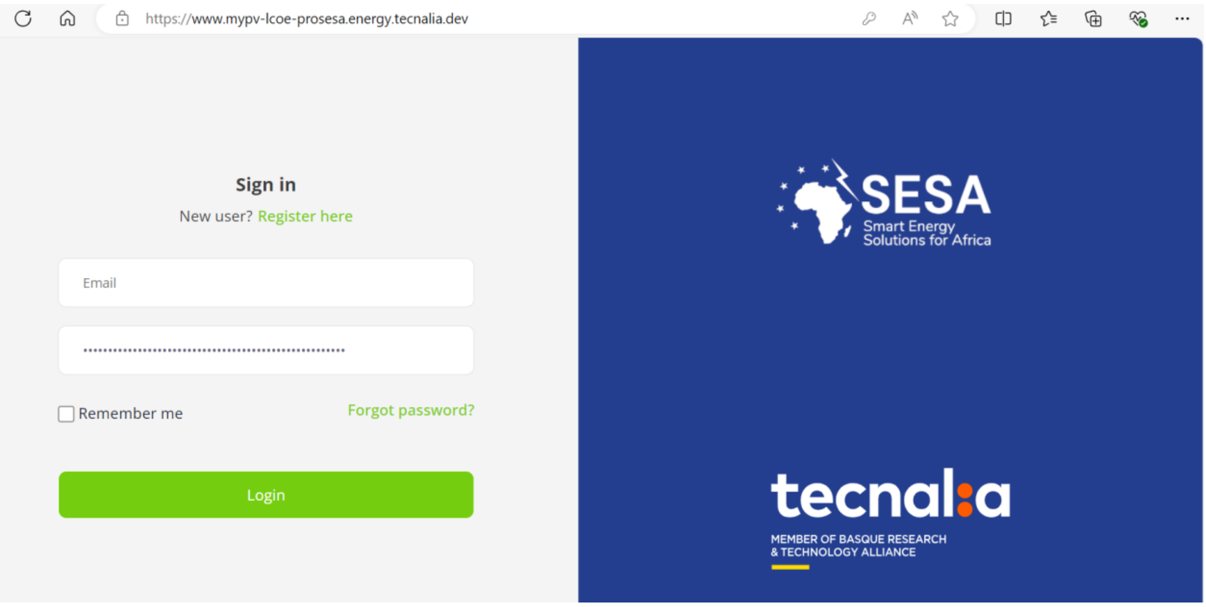


Figure 2.1 Login/register in the LCOE& climate PVTool web page

After login, user can choose between two options: ***Create new project+*** or ***Select*** one created and saved before:

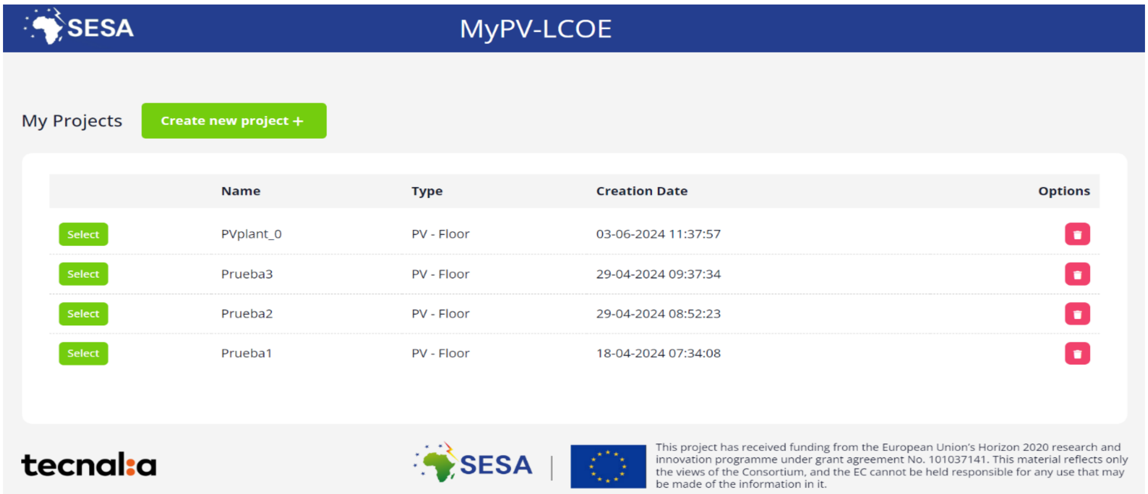


Figure 2.2 Choose between create a new project or select one already created

2.1.2. Create a new project & Introduce the input information

When user creates a new project, he/she should give it a ***Name*** and select the ***Type*** of PV plant (***PV floor*** or ***PV Floating***)

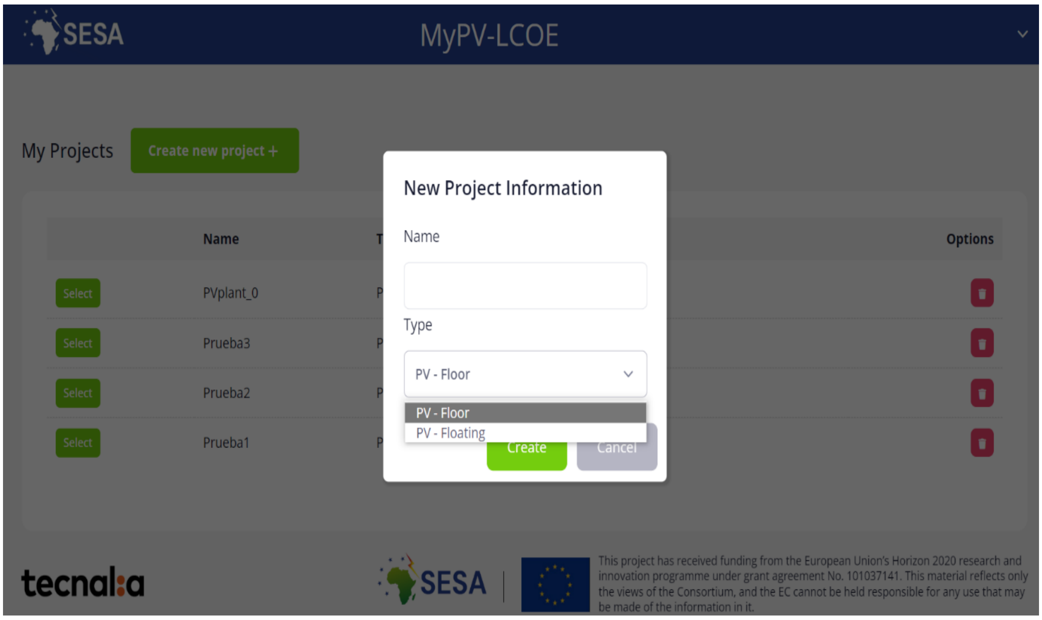


*Figure 2.3 Create a new project (give a **Name** a select the **Type** of PV plant*

If user decides to create a new project the following input data user should be introduced:

1. **Energy production:** This input data is required for the energy production assessment of PV plant in the first year of life, year 0, just after installation. Future years production will be corrected with the module degradation rates.
2. **Weather**. File with information for every hour about irradiation and ambient temperature in the plane of array.
3. **Financing**. Input data about the inflation and cost of investment
4. **CAPEX**. Capital Expenditure in year 0 for the PV plant.
5. **OPEX**. Operation Expenditure for every year for the PV plant.

These input data are introduced through different screens. An input data progress bar (Figure 2.) indicates user which type of input data is introducing.

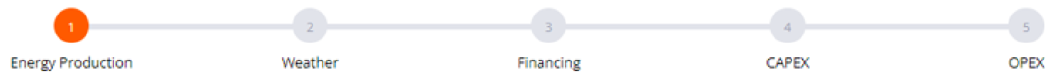


Figure 2.4 CREATE NEW PROYECT-> Input data progress bar

2.1.2.1. Energy production

These input data are required for the energy production assessment of PV plant in the first year of life (year 0) just after installation.

Table 2.1 Input data: 1. Energy production

ENERGY PRODUCTION	Parameter	Default value	unit	Comment/ description
System description	Front side efficiency		%	Extracted from PV module datasheet
	Temp coeff Pmax	-0,25	%	Extracted from PV module datasheet
	NOCT	44	ºC	Extracted from PV module datasheet
	DC Total Power (P)		kWp	Provided by user - Design
	Module bifaciality		%	Extracted from PV module datasheet
	Backside irradiance		%	Provided by user – Design
DC losses modelling (%)	Soiling	0,50	%	Provided by user
	Module mismatch	1,00	%	Provided by user
	Diodes and connection	0,75	%	Provided by user
	Low irradiance	1,00	%	Provided by user
	DC wiring	2,00	%	Provided by user
	Tracking error	0,50	%	Provided by user
	DC Availability	0,00	%	Provided by user
AC losses modelling	Inverter Nom power		kW	Calculated from DC power and DC/AC ratio
	Inv op. consumption	0,00	kW	Provided by user
	Inv night consumption	0,00	kW	Provided by user
	Inv efficiency		%	Extracted from PV inverter datasheet
	AC wiring	1,50	%	Provided by user
	Transformers no-load		kW	Provided by user
	Transformers load		%	Provided by user
	AC availability	0,50	%	Provided by user
Module Degradation (%)	Year 1	2,00	%	Provided by user
	Year2-year 5	0,50	%	Provided by user
	Year6-year25	0,50	%	Provided by user
	Year 26-year35	0,50	%	Provided by user
Inverter power adjusted with bifaciality factor	DC/AC ratio	1,20	X/1	Provided by user – Design

Values included are default values and can be kept if no other data are available.

Figure 2. shows the screen where user can introduce all input parameters for energy production, moving down the scrollbar at the right side.

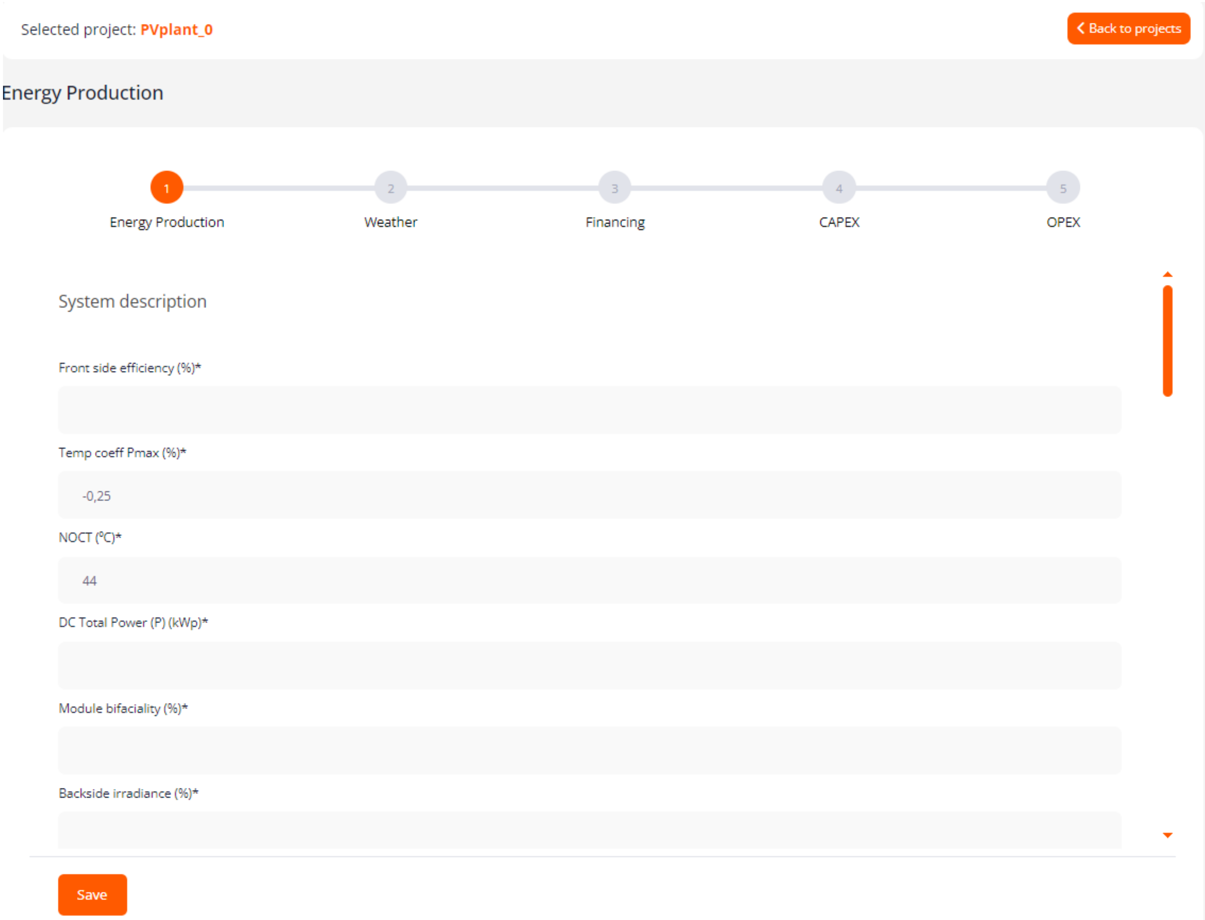


Figure 2.5 CREATE NEW PROYECT-> Input data: 1.Energy production (screenshot 1)

2.1.2.2. Weather

According to the location, user should upload the climatic file with the radiation data for the adequate location (as default option, ***.tmy*** or ***.csv*** files are required).

This file contains information of radiation and temperature for each of 8.760 hours in one year. The Mandatory fields are: "***Time***" (data & hour) ***radiation*** (G(i)) and the ***temperature*** (T2m). (see Table 2.2).

The file can be obtained:

- File ***.tmy*** or ***.csv*** customized by the user, with 8760 values, for G and T, one raw per hour.
- From PVGIS Programme (*JRC Photovoltaic Geographical Information System (PVGIS) - European Commission (europa.eu)* (In the figure bellow you may find details on how to download the requires file)

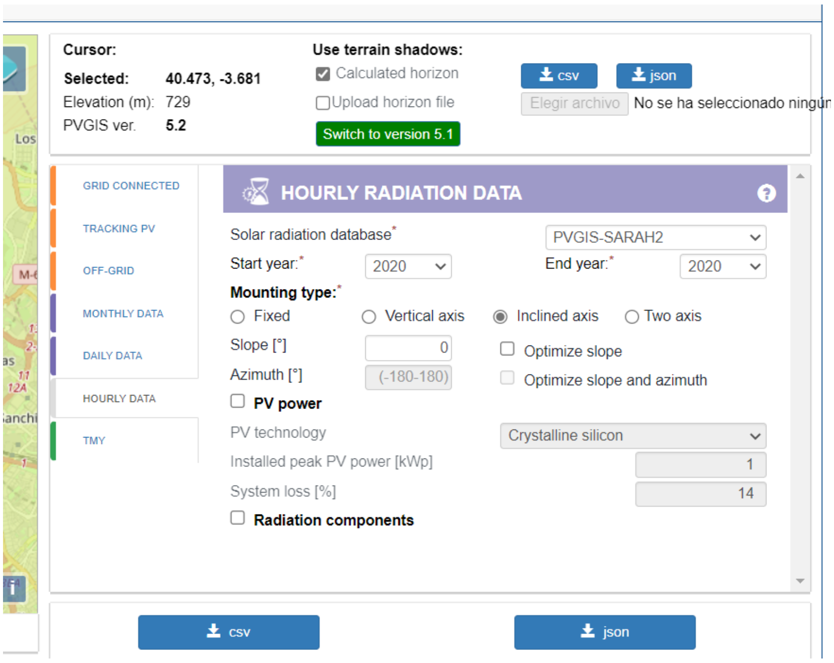


Figure 2.6 Details on how to download the required file of Weather from PVGIS

Table 2.2 Input data: 2. Weather – example of Information of a climate file (radiation and Temperature for each hour of the year)

Hour	Geff Front [W/m2]	Dry-bulb Temp [ºC]
1	0	2,33
2	0	2,07
3	0	0,92
4	0	0,27
5	0	-0,08
6	0	-0,40
7	0	-0,72
8	0	-1,82
9	270,79	-1,64
10	632,36	0,01
11	609,62	3,32
12	511,26	5,86
13	468,39	8,11
14	498,88	9,81
15	573,05	10,84
8784	0	3,22

Once the Weather file is selected from PC, user should click ***Upload*** bottom.

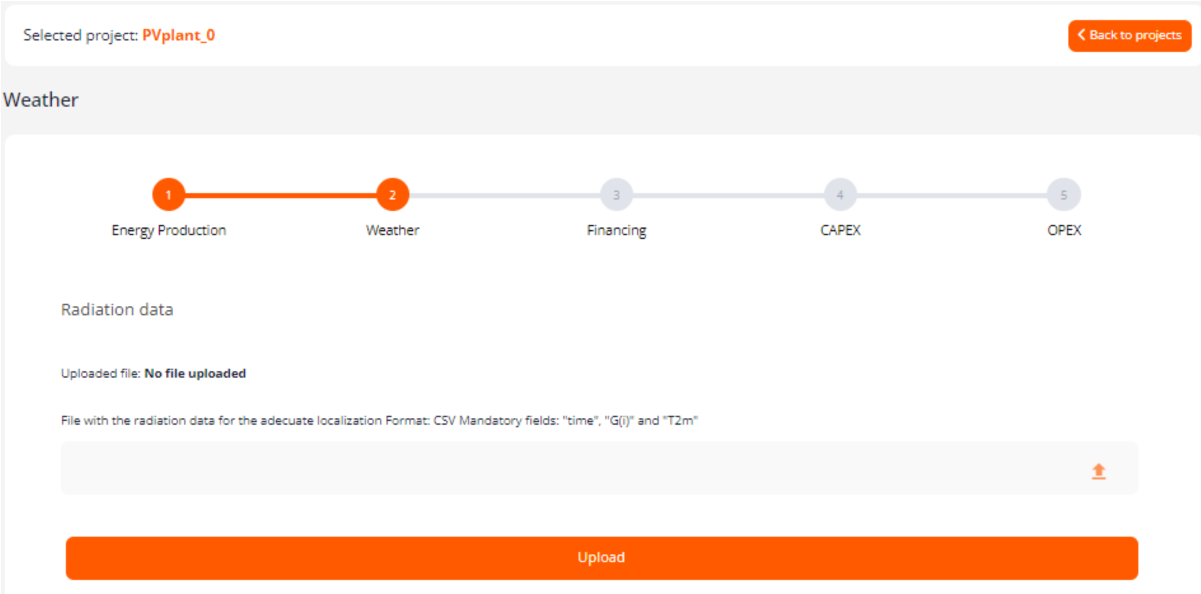


Figure 2.7 CREATE NEW PROYECT -> Input data: 2. Weather

2.1.2.3. Financing

Informative formulae for user of the LCOE tool. The required parameters are just Nominal **W_{Acc}** and **inflation.**

User is responsible on the procedure on how to calculate WACC.

Table 2.3 Input data: 2. Weather – example of Information of a climate file (radiation and Temperature for each hour of the year)

FINANCING			
Parameter	Default value	unit	Comment/ description
WACC $_{Nom}$	-	%	
Inflation	-	%	

$$\text{WACC}_{\text{Nom}} = \frac{D}{D+E} * (1-T) * k_d + \frac{E}{D+E} * k_e$$

with E = equity financing; D = % debt financing;
k_d= interest rate of debt financing; k_e = equity financing; T = Corporate Tax rate

$$\text{WACC} = \frac{E}{V} * Re + \frac{D}{V} * Rd * (1 - Tc)$$

$$\text{WACC}_{\text{Real}} = \left(\frac{1+\text{WACC}_{\text{Nom}}}{1+\text{Inflation}} - 1\right)$$

Where:

Re = cost of equity
Rd = cost of debt
E = market value of the firm's equity
D = market value of the firm's debt
V = E + D = total market value of the firm’s financing (equity and debt)
E/V = percentage of financing that is equity
D/V = percentage of financing that is debt
Tc = corporate tax rate

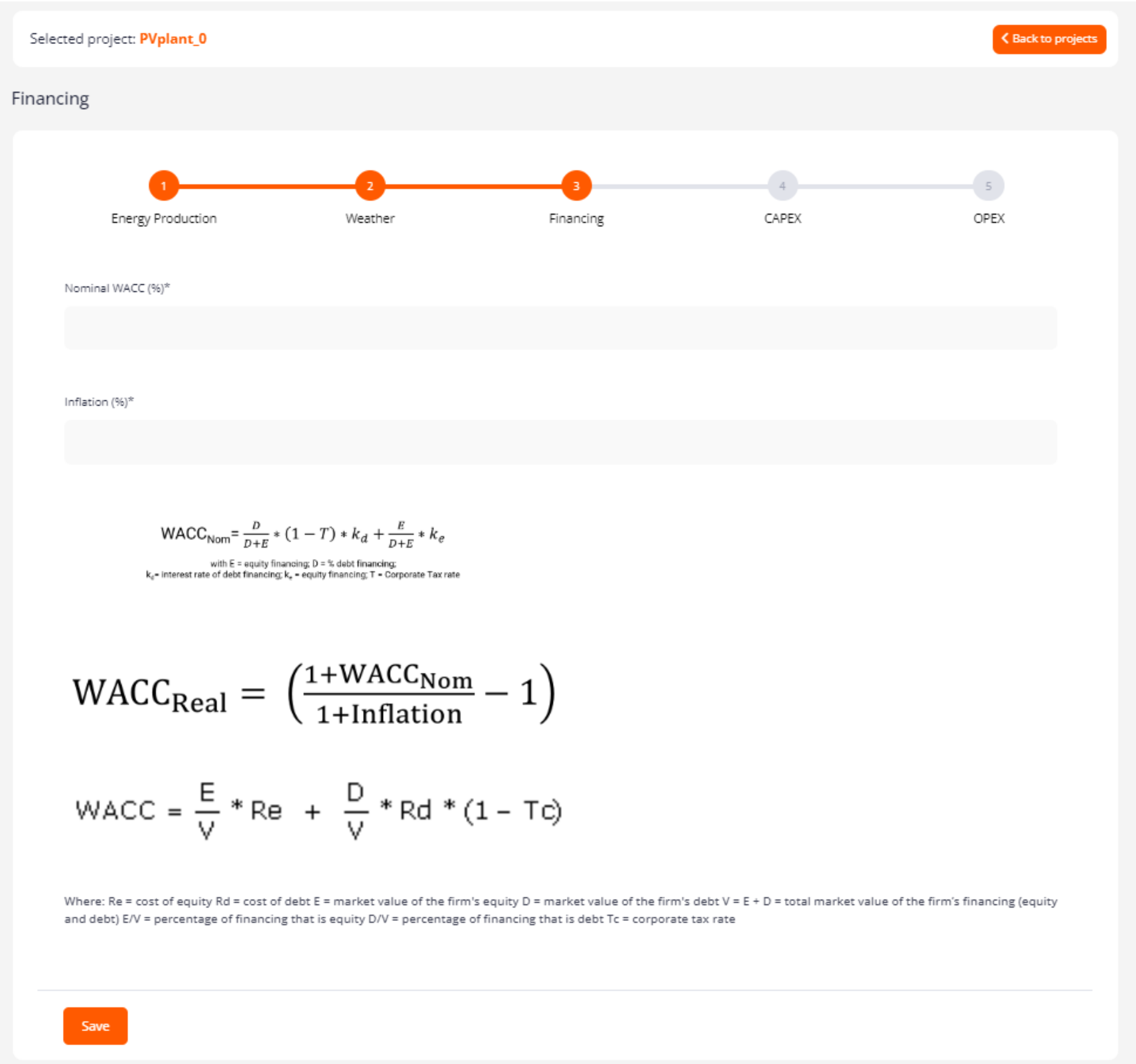


Figure 2.8 CREATE NEW PROYECT-> Input data: 3. Financing

2.1.2.4. CAPEX

For the CAPEX, the user can select 2 options:

1. Total values per budget chapter (K€)
2. Individual value as €/Wp or simular.

If both are present, the default values will be individual ones.
If individual values are 0, then total values will be considered.

User can introduce the information values of CAPEX in total (k€) or values per Wp (€/Wp).

Table 2.4 Input data: 3. CAPEX

CAPEX			
Parameter	**kEUR (TOTAL)**	**Values (€/Wp)**	**Comment/ description**
PV MODULES			
TRACKERS (Including foundations)			
Conversion Unit (Inverters)			
BOP			
ELEC. SUBSTATION & INTERCONNECTION			
E&C COST			E&C Cost: Internal and External Cost for Engineering and Construction Activities (Design, Studies, Personnel on site, Travel and Lodging of the Internal People involved in the Construction Activities)
CONTINGENCY			
LAND	0,00		No need to be provided
DEVELOPMENT COSTS			Development Cost: Any cost and effort related to the development of the Projects (Permits, Lands, Fees, etc).
TOTAL	*		*This value is the sum of the previous one in the case of total

Is Land rented? (YES/NO)	**YES/NO**
Land cost (purchase) k€/Ha	
Land cost (annual fee, rent) k€/Ha	

Sometimes, prices are obtained in US dollars. So the exchange between dollar and EURO is provided by the tool.

EUR/USD	1,08331

The following figures show the screen where user can introduce all input parameters for CAPEX in total (k€) (Figure 2.) or in values per Wp (€/Wp) (Figure 2.), moving down the scrollbar at the right side.

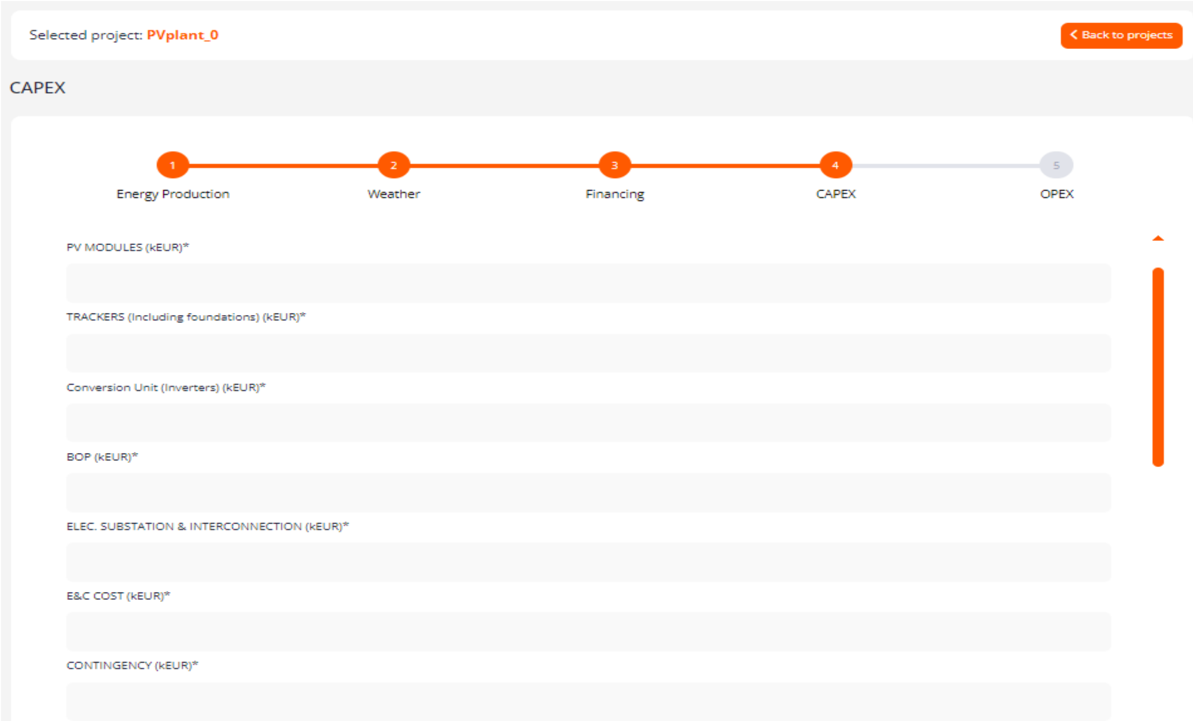


Figure 2.9 CREATE NEW PROYECT-> Input data: 4. CAPEX in total (k€)

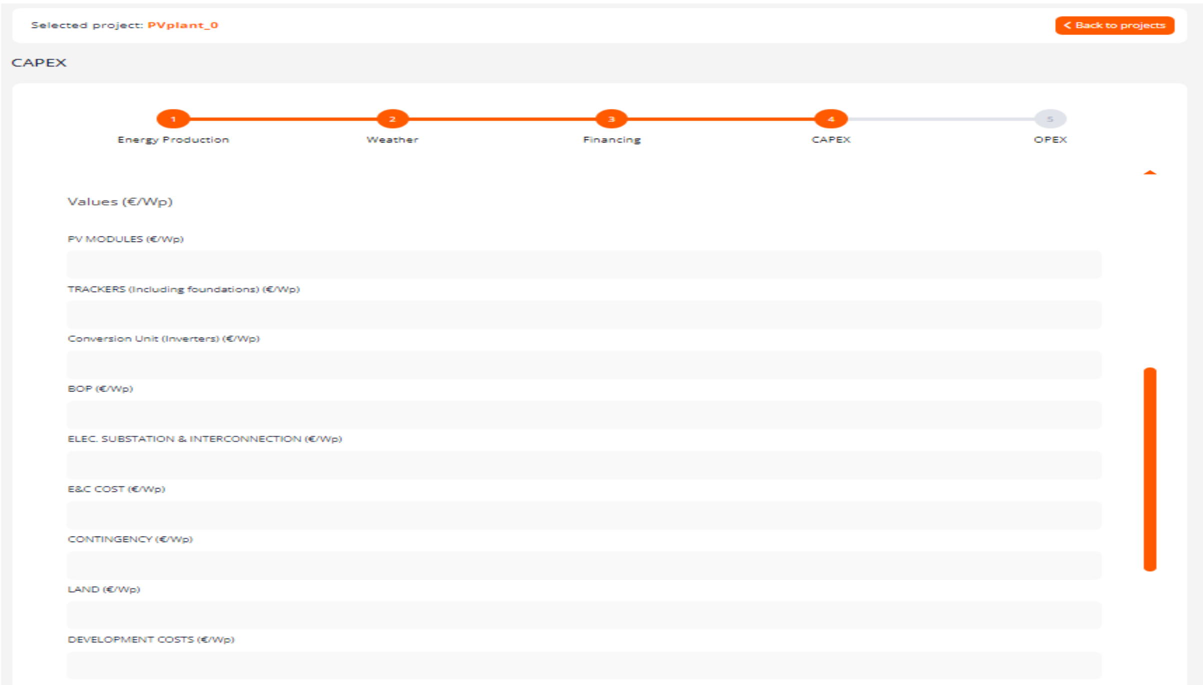


Figure 2.10 CREATE NEW PROYECT-> Input data: 4. CAPEX values per Wp (€/Wp)

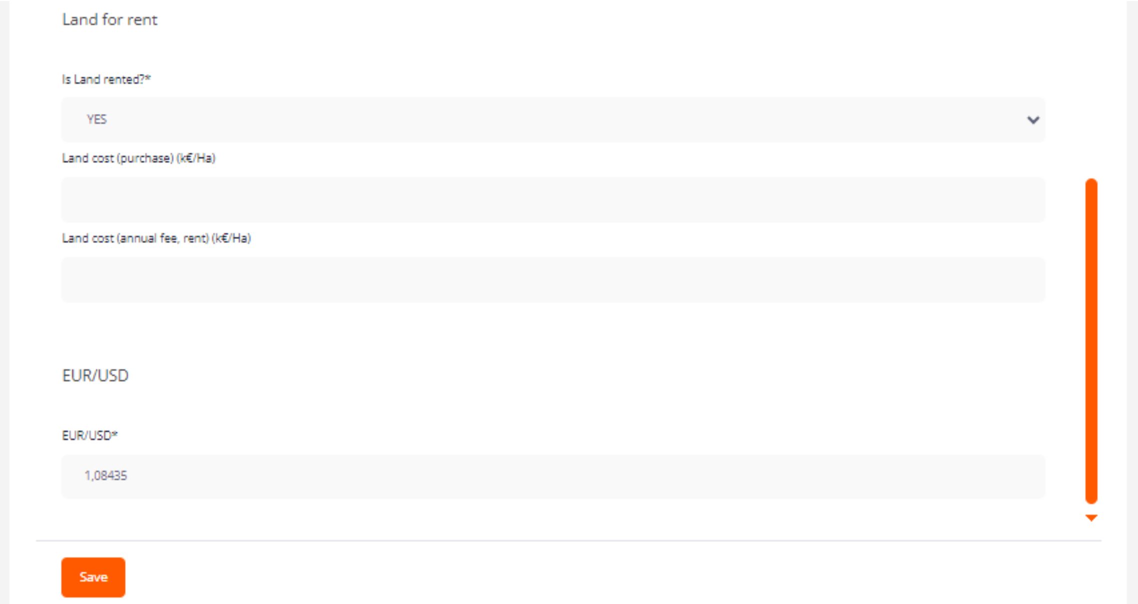


Figure 2.11 CREATE NEW PROYECT-> Input data: 4. CAPEX Land for rent + €/USD

2.1.2.5. OPEX

The user fills the parameters for "Variable for Year 1 **(Y1)**". For the rest of Years, the user must indicate if values remain as in Y1 or change, or simply there aren't.

In the first case the tool automatically fills the parameters of the rest of the years from Year 1 to Year X (**Yx**) where x is defined by the user. After that the user could modify any value for each of the year.

Table 2.5 Input data: 3. OPEX

O&M

OPERATION SERVICES	Y1
Basic electromechanical tasks	0,35
HV Lines+ SUBSTATION	0,25
Tracker inspection	0,38
Grass cutting	
Module cleaning	0,30
TOTAL SERVICES (kEUR/MW)	**1,28**

MAINTENANCE SERVICES (KEUR/MW)	Y1
Inverter Preventive Maintenance	1,24
Inverter Corrective Maintenance	
Tracker Predictive Maintenance	
TOTAL MAINTENANCE SERVICES (KEUR/MW)	**1,24**

MATERIAL AND OTHER MACHINES (kEUR/MW)	Y1
Material and forniture (kEUR /MW)	1,50
Inverter Replacement	
Tracker maintenance (replacement control + actuator)	0,10
SCADA REPLACEMENT	
CLEANING MACHINE	
ICT COST	0,34
TOTAL MATERIAL AND OTHER MACHINES (kEUR/MW)	**1,94**

TAXES	Y1
Taxes and charges (kEUR /MW)	

OTHER COSTS (kEUR /MW)	Y1
Data Transmission	0,04
Energy Consumption	0,60
Site Maintenance	0,30
Surveillance	0,70
TOTAL OTHER COSTS (kEUR /MW)	**1,64**

PERSONNEL COSTS /MW	Y1
Supervisor	
Assistant	0,47
TOTAL PERSONNEL COSTS /MW	**0,47**

OTHER COSTS FOR OPERATION	Y1
Asset Management (kEUR/MW)	
Insurances (kEUR/MW)	
Monitoring (kEUR/MW)	
TOTAL OTHER COSTS FOR OPERATION	

LAND COST (se calcula)	Y1
Land Rental (kEUR/Ha)	2,7

DISMANTLING	Y1
Dismantling and Recycling Costs	

Ocuppance

Oucpación de terreno — 1,8 Ha/MWp

Plant (84.73 MWdc)	P mod [W]	Modules q.ty	Delta	Land [ha/MWdc]
STD REF	340	249200	-	2
GOPV initial	390	217257	-12.8%	1.7
GOPV actual	370	229000	-8.1%	1.8

Lifetime

Años de operación — 35 años

Variables for the dismantling and recycling costs	DC_T	
	IC_T	
	MR_T	15
	LF_T	
	SV_T	
	LV_T	
	r	
	T	

NDC_{PV}	15,00	kEUR/MW

Variables for the dismantling and recycling costs

- NDC_{PV}= present value of the net cost to decommission a PV power plant
- DC_T + IC_T = Direct cost (labor, equipment) and indirect cost of PV plant de-installation, demolition, recovery, and land reclamation in year T.
- MR_T = PV module recycling cost in year T.
- LF_T = Landfill disposal cost in year T, including landfill tipping fees and hauling, of non-salvageable material.
- SV_T = Scrap value of steel, copper and aluminum recovered during PV solar field and power equipment removal and sold to recyclers at prices prevailing in year T.
- LV_T = Value of reclaimed land in year T.
- *r* = Rate of annual discount applied to costs and revenues realised in year T.

In the last year, negative sign means incomes. Residual value, sales of final product

Figure 2. shows the screen where user can introduce all input parameters for energy production, moving down the scrollbar at the right side.

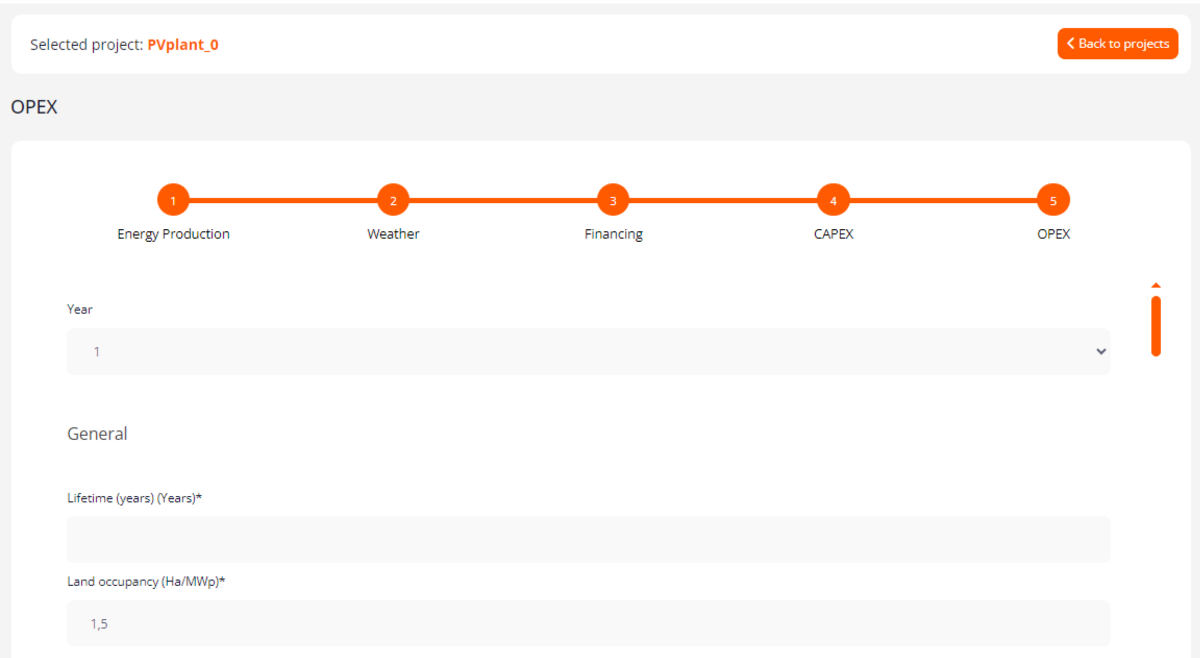


Figure 2.12 CREATE NEW PROYECT-> Input data: 5.OPEX (screenshot 1)

2.1.3. View of outputs

After calculation user is able to download the results calculated setting the mouse on the user e-mail (at the top right side of the scream) as Figure 2. shows.

In the same place, user can close the session.

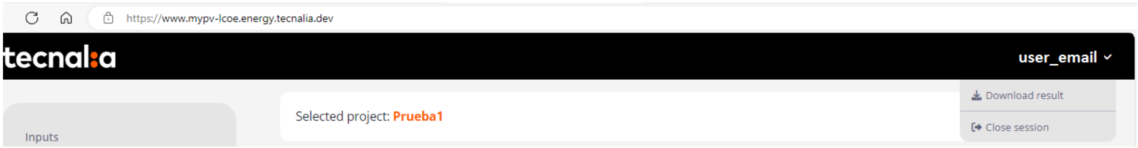


Figure 2.13 Download results

Furthermore, user is able to visualize the results selecting the specific output in the menu at the left side of the screen.

2.1.3.1. System Outputs

System outputs are referred to energy outputs. The energy losses due to different loss source is also indicated. Main parameter in this chapter is Performance Ratio (PR), which indicates the quality of PV plant design.

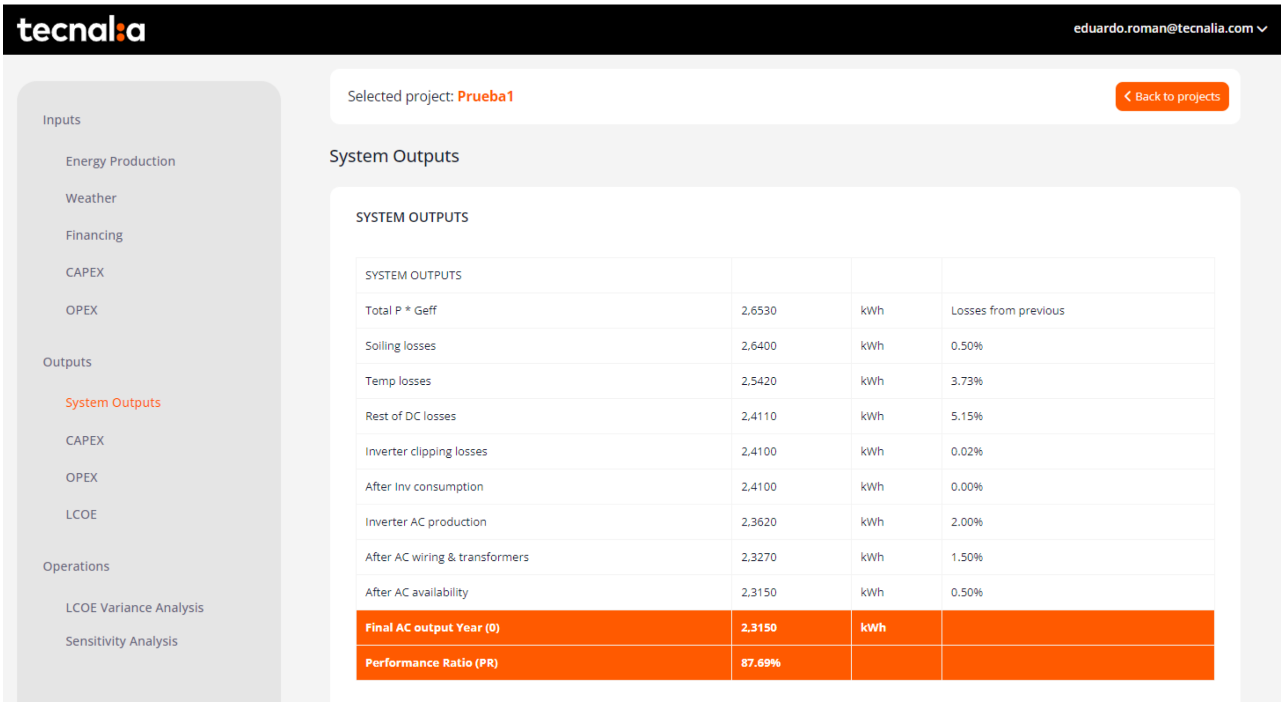


Figure 2.14 Outputs: System Outputs

2.1.3.2. CAPEX

For the CAPEX, the total costs are displayed, both in kEUR and also in EUR/Wp.

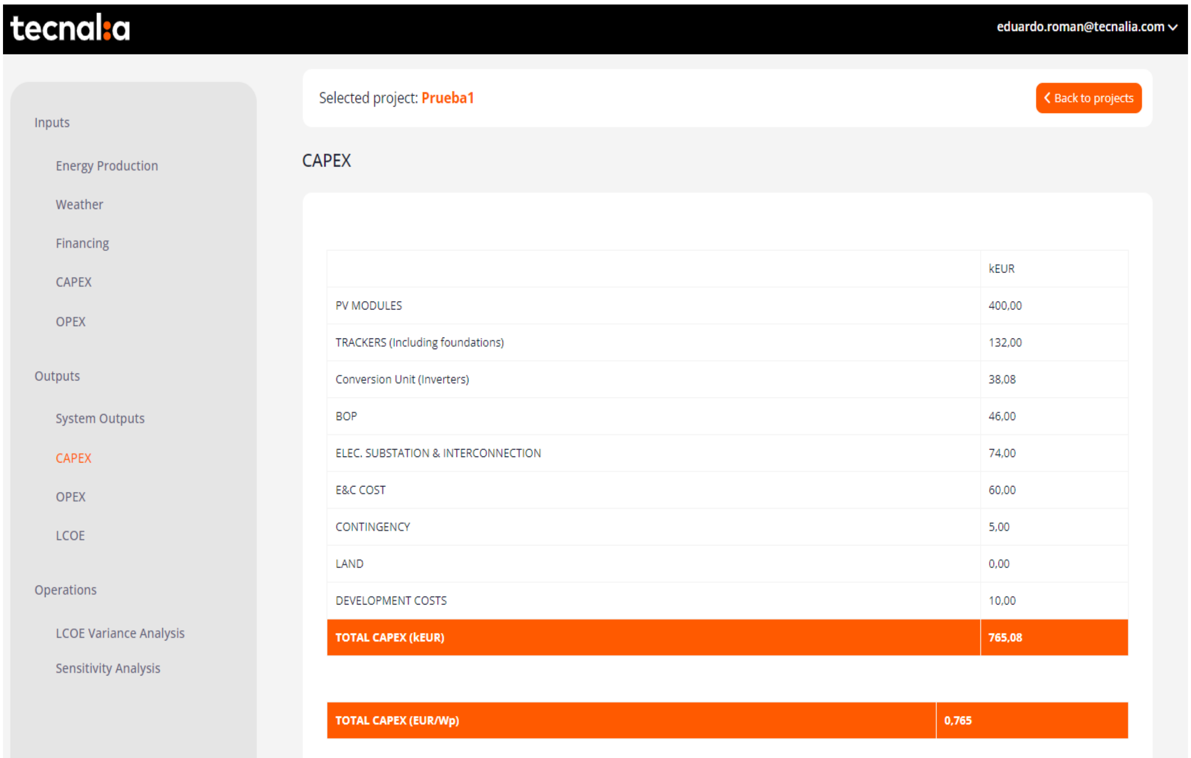


Figure 2.15 Outputs: CAPEX

2.1.3.3. OPEX

OPEX values are presented by year, so final result is displayed in kEUR/MW.year and kEUR/year.

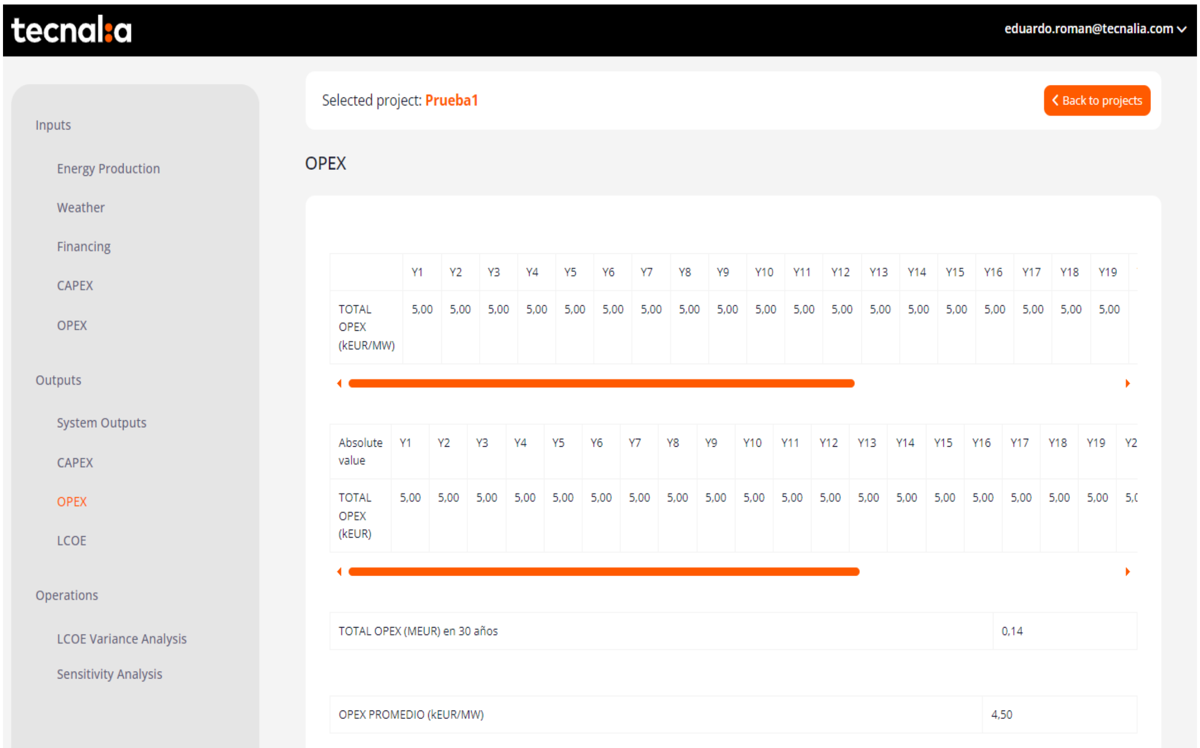


Figure 2.16 Outputs: OPEX

2.1.3.4. LCOE

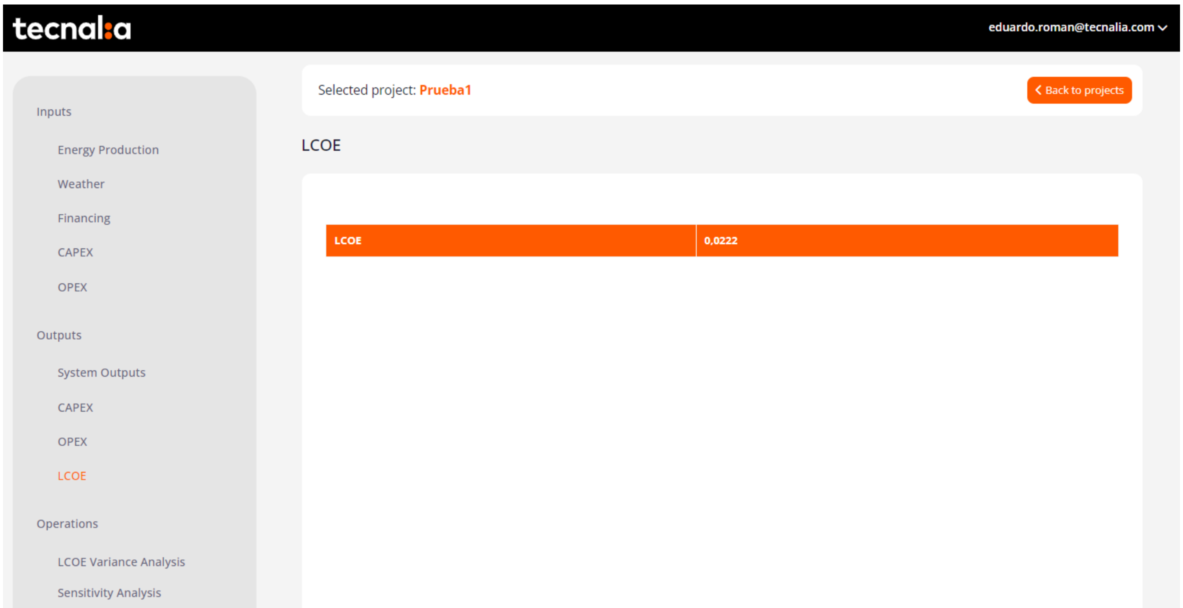


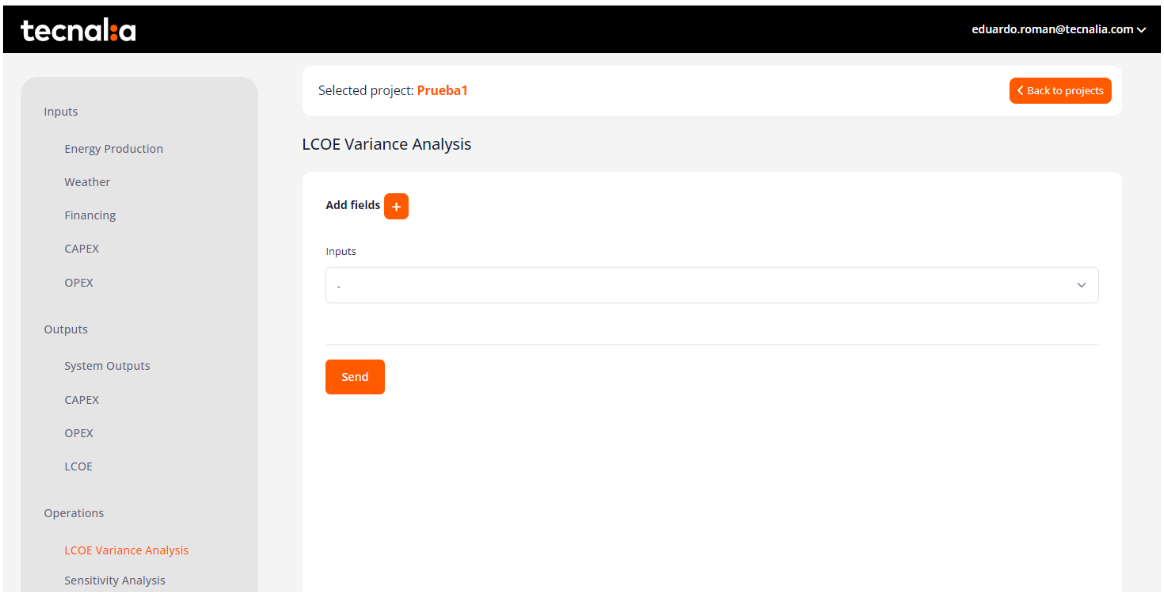
Figure 2.17 Outputs: LCOE

2.1.4. Other operations

2.1.4.1. LCOE Variants

Operations come after design of PV plant is plotted and LCOE value calculated, as an initial picture of the PV plant design. Sometimes the user would like to know what if… what would be LCOE value if such PV component is replaced, or if we use this PV module instead of this one, or if we use this O&M strategy that is cheaper… The tool offers the possibility to modify 2 variables at the same time, indicating the limits for the variation and the step for each iteration. It is what we call sensitivity analysis, and the tool is capable of provided several LCOEs values at the same time, by combining the variables subject to analysis.

An example is shown in the following images, in which the inflation and nominal WACC are modified simultaneously.



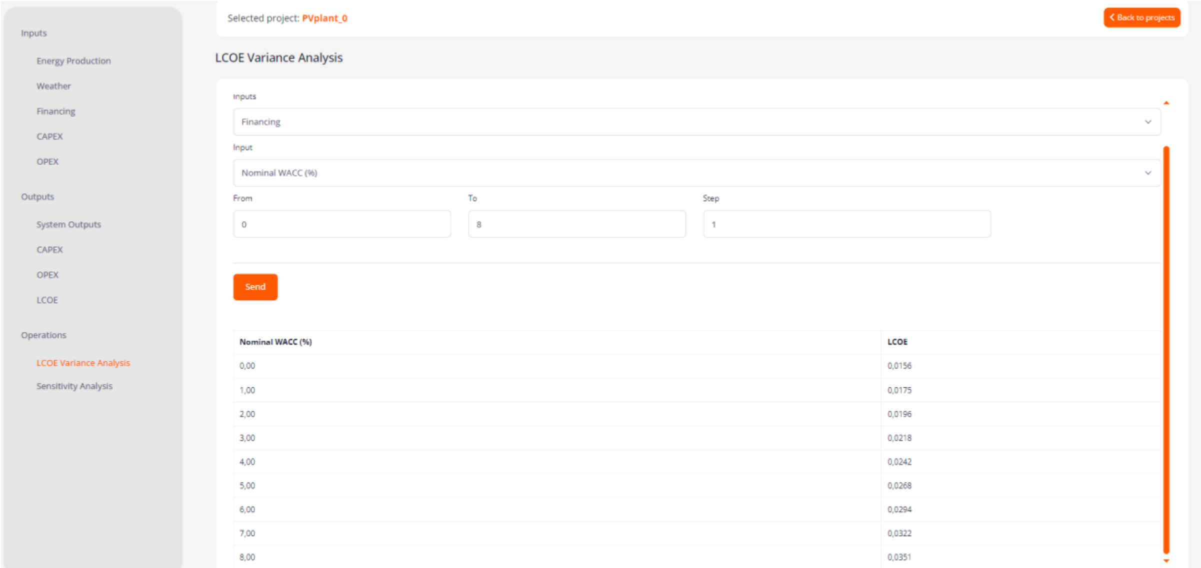
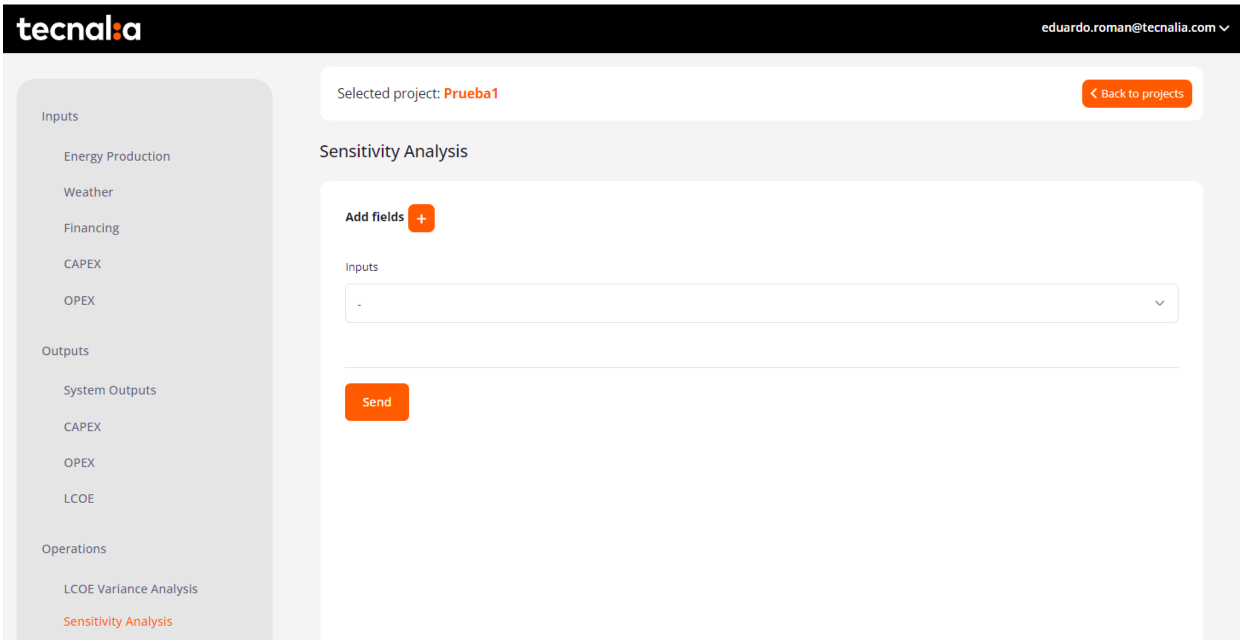


Figure 2.18 Operation: LCOE Variance Analisys

2.1.4.2. Sensitive Analysis

The way in which results are provided can be more user-friendly, and for sensitivity analysis a horizontal bars diagram is frequently used. In this case, the starting point is the case0, whose LCOE value has been initially calculated. Then, the user can modify any number of parameters and execute again the LCOE analysis. In this case, contrary to the LCOE Variations, each parameter is modified individually and LCOE calculated, so the effect of just one modification is plotted. The advantage is that in one graph the user can display the effect of LCOE of so many parameters as he wishes, without repeating again and again the calculation. In blue positive results are displayed, and negative in red (negative means that LCOE is worsened).



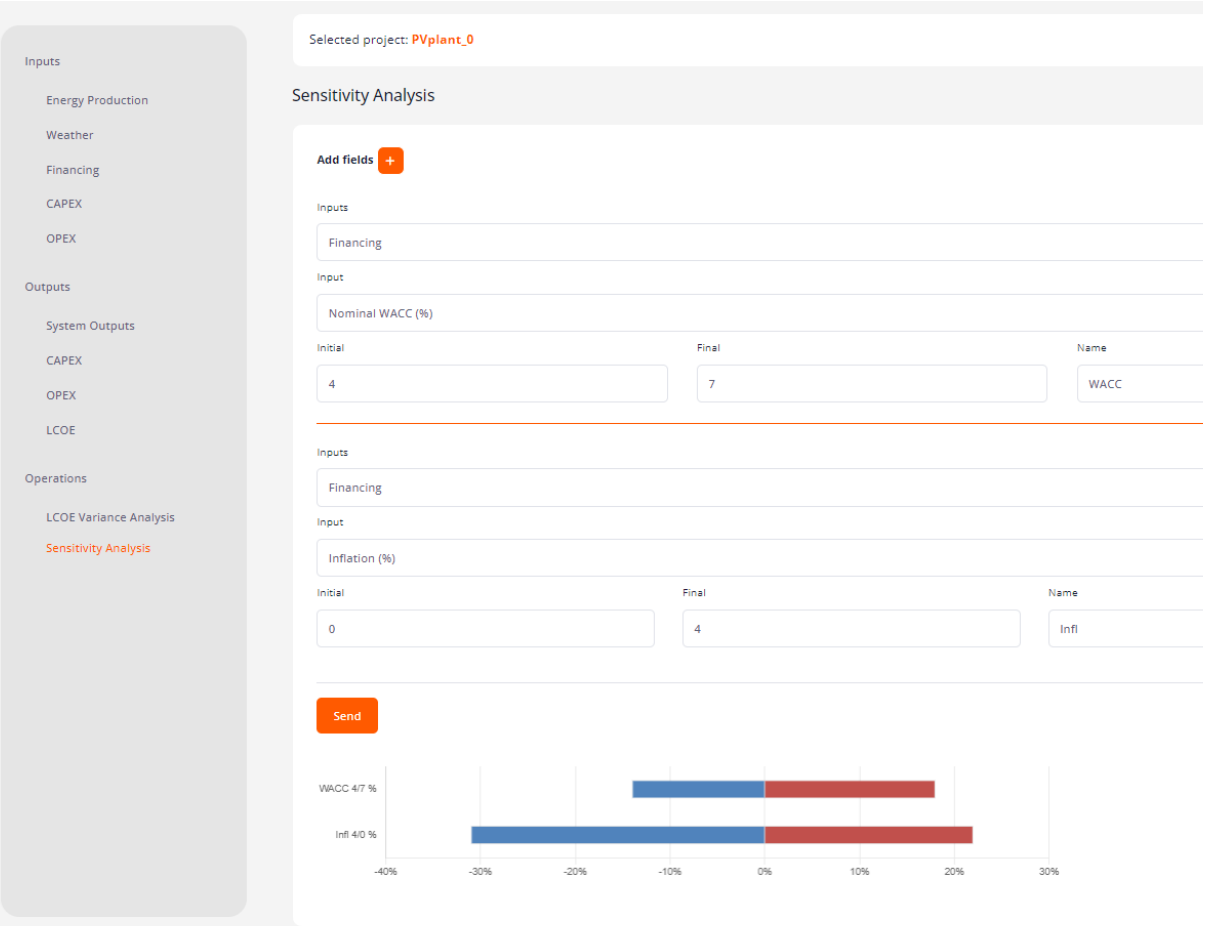


Figure 2.19 Operation: sensitivity Analisys

By clicking on the image, the graphic can be downloaded.

2.1.5. View a project already saved

User can is able to ***Select*** one project created and saved before, and visualize the input and output data by selecting the specific input or output in the menu in the left side of the screen.

For input data:

1. Energy production:
2. Weather
3. Financing
4. CAPEX
5. OPEX

The parameters are the same of Figure 2.5 CREATE NEW PROYECT-> Input data: 1.Energy production (screenshot 1) and the following, but the appearance changes a little bit as the input data progress bar (Figure 2.4) disappears, and the menu at the left side of the screen appears.

For output data the scream s are the same that figures from Figure 2. to Figure 2. in section **2.1.3 View of outputs.**

Other operations (see section **2.1.4 Other operations**) are always possible to implement / repeat.

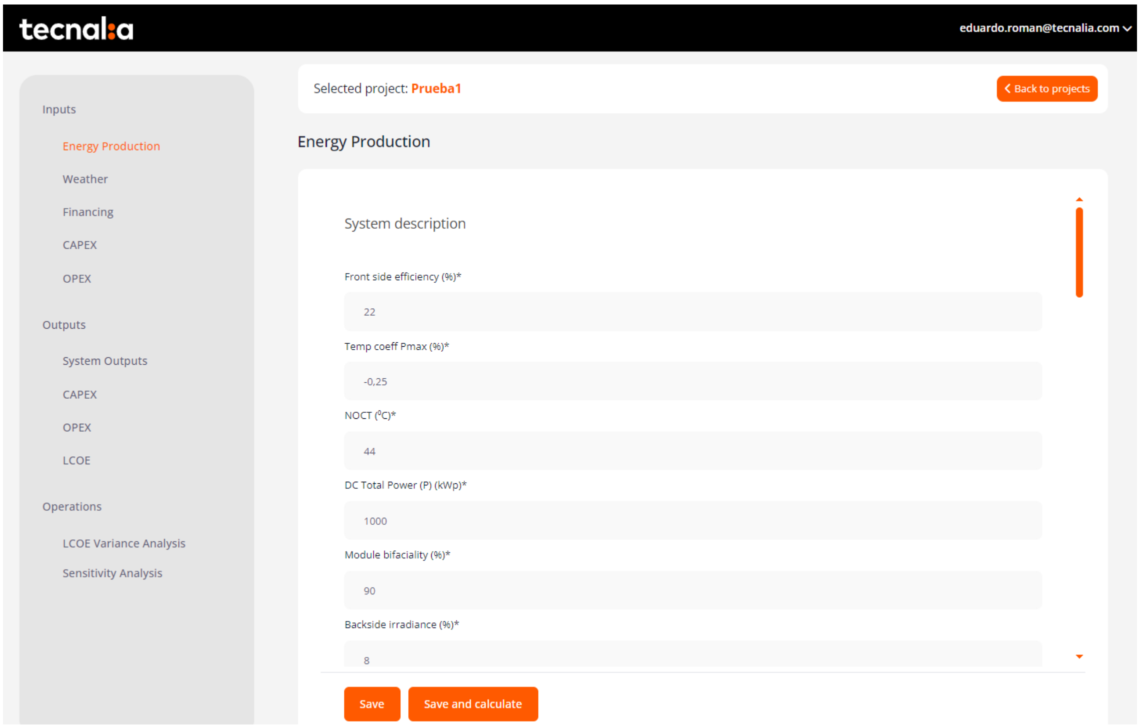


Figure 2.20 Input data: 1.Energy production (screenshot 1)

2.2. Climate Projections Assessment Module

This module is a python code that applies climate change projections to any target year that can be downloaded from PVGIS (https://re.jrc.ec.europa.eu/pvg_tools/es/, last accessed May 2024). More specifically, it projects the hourly time series for a given year to different future climate scenarios and time horizons, as explained in chapter 0. This allows to introduce these resulting projected time series in the LCOE Assessment Module to calculate the LCOE of the designed PV system in the context of future climate.

2.2.1. Input data

The climate information describing baseline scenario (i.e. the past observed period) is extracted from PVGIS (https://re.jrc.ec.europa.eu/pvg_tools/es/, last accessed May 2024) following the instructions given in section 2.1.2.2. From this site the user can download the specific climate variables that are needed by the LCOE Assessment Module and, hence, are projected by this Climate Projections Assessment Module. Two files must be downloaded from PVGIS by the user for the location of interest:

- the hourly time series of the target year (e.g. 2020) and
- the full hourly time series that will be used to contextualise the target year within the current climate. In this second case, the available time series in PVGIS at this moment is 2005-2020, so the module will need all these years at hourly scale for the location of interest.

The files must be downloaded in CSV format.

For describing the future scenarios, user interaction is not needed. The climate information is automatically extracted from CORDEX by this Climate Projections Assessment Module. The python code automatically downloads the data from the Copernicus Climate Data Store (CDS) (https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cordex-domains-single-levels?tab=overview, last accessed May 2024), so the user does not need to provide anything in this sense.

Copernicus offers information from several climate models (as explained in chapter 1.3.2) that will be downloaded automatically by this module (available models for Africa and Europe in Table 2.6 and **¡Error! No se encuentra el origen de la referencia.**Table 2.7). In further steps, the module will guide the user and simplify the selection of preferred models for LCOE assessment (see 2.2.4).

Table 2.6 Models for Africa available for all the scenarios and horizons

GCM	RCM	Ensemble member
ichec_ec_earth	mpi_csc_remo2009	r12i1p1
ichec_ec_earth	smhi_rca4	r12i1p1
miroc_miroc5	smhi_rca4	r1i1p1
mohc_hadgem2_es	knmi_racmo22t	r1i1p1
mohc_hadgem2_es	smhi_rca4	r1i1p1
mpi_m_mpi_esm_lr	mpi_csc_remo2009	r1i1p1
mpi_m_mpi_esm_lr	smhi_rca4	r1i1p1
ncc_noresm1_m	smhi_rca4	r1i1p1

Table 2.7 Models for Europe available for all the scenarios and horizons

GCM	RCM	Ensemble member
cnrm_cerfacs_cm5	cnrm_aladin63	r1i1p1
cnrm_cerfacs_cm5	knmi_racmo22e	r1i1p1
ichec_ec_earth	clmcom_clm_cclm4_8_17	r12i1p1
ichec_ec_earth	dmi_hirham5	r3i1p1
ichec_ec_earth	gerics_remo2015	r12i1p1
ichec_ec_earth	knmi_racmo22e	r12i1p1
ichec_ec_earth	smhi_rca4	r12i1p1
mohc_hadgem2_es	dmi_hirham5	r1i1p1
mohc_hadgem2_es	gerics_remo2015	r1i1p1
mohc_hadgem2_es	knmi_racmo22e	r1i1p1
mohc_hadgem2_es	smhi_rca4	r1i1p1
mpi_m_mpi_esm_lr	mpi_csc_remo2009	r1i1p1
mpi_m_mpi_esm_lr	mpi_csc_remo2009	r2i1p1
mpi_m_mpi_esm_lr	smhi_rca4	r1i1p1
ncc_noresm1_m	gerics_remo2015	r1i1p1
ncc_noresm1_m	smhi_rca4	r1i1p1

2.2.2. Climate variables and scenarios

As mentioned in chapter 0, the variables considered by the LCOE assessment Tool are ambient temperature and radiation. The specific climate variables projected by this Climate Projections Assessment Module to be used by the LCOE Module are the following:

- 2 m air temperature in degree Celsius (identifier: t2m) and
- global irradiance on the inclined plane (plane of the array) (W/m2) (identifier: G(i)).

The rest of the variables that are also contained by the CSV files downloaded from PVGIS are ignored and keep as they are in the original file.
As described in chapter 0, to account for the uncertainty in the future climate scenarios, the module considers three climate scenarios (pathways) that correspond to different GHG emissions: RCP2.6 (low emissions), RCP4.5 (intermediate emissions) and RCP8.5 (very high emissions). Each of these scenarios is, at the same time, analysed for three future time horizons: 2021-2040, 2031-2050, and 2041-2060. As already mentioned in 0, these periods are selected to account for the whole lifetime of the photovoltaic power plant.

2.2.3. Running the module

Originally, the module is available as a gitlab repository that can be cloned and run. However, the idea is to provide an online connection to the service, so users do not need to install python or even have any computational power to get the results.
The service will ask for two input CSV files for a given location (target year + time series, as described in section 2.2.1) that must be provided with the same name and structure as is provided by PVGIS. Then the service will return a ZIP file that will contain all the projected files described in section 2.2.4.

2.2.4. Results structure

The results will be provided in a ZIP file that will contain the following folder (the blurred characters correspond to the location):

Timeseries_[illegible]_SA2_i0deg_2020_2020

As can be seen the name of the folder is equal to the one provided by PVGIS. Inside this folder we have one subfolder per climate scenario:

baseline
rcp-2-6
rcp-4-5
rcp-8-5
PVGIS_[illegible]_202001010000-202012312300_G(i).html
PVGIS_[illegible]_202001010000-202012312300_T2m.html

The 'baseline' contains the original time series downloaded from PVGIS (the target year). The only change in this file is its name which now follows the internal naming.

PVGIS_[illegible]_202001010000-202012312300_-.csv

In the rest of the folders that correspond to each of the future climate scenarios we will find the time series of each model for each horizon. As we said the 9 available scenarios are the combinations of:

- Scenarios: RCP2.6 / RCP4.5 / RCP8.5
- Horizons: 2021-2040 / 2031-2050 / 2041-2060

The naming convention followed by the files can be interpreted as:

```
standard_name = (
    f'CORDEX_'
    f'{location}_'
    f'{horizon}_'
    f'-_'
    f'{global_model}_'
    f'{regional_model}_'
    f'{ensemble_member}_'
    f'{scenario}_'
    f'{baseline_time_series}'
)
```

where:

- **location** represents the coordinates of the point of interest.
- **horizon** represents the future horizon.
- **global_model** defines the name of the Global Circulation Model (GCM)
- **regional_model** defines the name of the Regional Climate Model (RCM)
- **ensemble_member** is the member of the GCM-RCM combination
- **scenario** is the name of the experiment
- **baseline_time_series** represents which hourly time series has been used as baseline (target year).

CORDEX_[redacted]_20210101-20401231_-_ichec-ec-earth_mpi-csc-remo2009_r12i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20210101-20401231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20210101-20401231_-_miroc-miroc5_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20210101-20401231_-_mohc-hadgem2-es_knmi-racmo22t_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20210101-20401231_-_mohc-hadgem2-es_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20210101-20401231_-_mpi-m-mpi-esm-lr_mpi-csc-remo2009_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20210101-20401231_-_mpi-m-mpi-esm-lr_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20210101-20401231_-_ncc-noresm1-m_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20210101-20401231_ranking_-_-_-_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_ichec-ec-earth_mpi-csc-remo2009_r12i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_miroc-miroc5_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_mohc-hadgem2-es_knmi-racmo22t_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_mohc-hadgem2-es_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_mpi-m-mpi-esm-lr_mpi-csc-remo2009_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_mpi-m-mpi-esm-lr_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_ncc-noresm1-m_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_ranking_-_-_-_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_ichec-ec-earth_mpi-csc-remo2009_r12i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_miroc-miroc5_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_mohc-hadgem2-es_knmi-racmo22t_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_mohc-hadgem2-es_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_mpi-m-mpi-esm-lr_mpi-csc-remo2009_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_mpi-m-mpi-esm-lr_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_ncc-noresm1-m_smhi-rca4_r1i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_ranking_-_-_-_rcp-8-5_202001010000-202012312300.csv

As explained, when dealing with future climate we need to deal with a huge uncertainty. This uncertainty is handled not only considering several climate scenarios, but also considering several climate models that typically generate diverging projections for the same scenario and horizon. To help the user decide which of the models is more interesting from their perspective, additional CSV files have been generated that include a ranking of models per scenario and horizon. The ranking is based on the theoretical change of the PV production that can be expected in that future climate. For example, this is the ranking for a location in Africa for the horizon 2041-2060 and RCP8.5:

experiment	gcm	rcm	ensemble_member	T2m_annual_diurnal_mean	G(i)_annual_sum	P_change_T2m (%)	P_change_G(i) (%)	P_change (%)
baseline				27.81	2604022	0.00	0.00	0.00
rcp-8-5	miroc_miroc5	smhi_rca4	r1i1p1	29.10	2607211	-0.32	0.12	-0.20
rcp-8-5	mpi_m_mpi_esm_lr	smhi_rca4	r1i1p1	29.13	2594970	-0.33	-0.35	-0.68
rcp-8-5	ncc_noresm1_m	smhi_rca4	r1i1p1	28.91	2585824	-0.27	-0.70	-0.97
rcp-8-5	mpi_m_mpi_esm_lr	mpi_csc_remo2009	r1i1p1	29.09	2584370	-0.32	-0.75	-1.07
rcp-8-5	mohc_hadgem2_es	smhi_rca4	r1i1p1	29.36	2582708	-0.39	-0.82	-1.21
rcp-8-5	ichec_ec_earth	smhi_rca4	r12i1p1	28.97	2565809	-0.29	-1.47	-1.76
rcp-8-5	mohc_hadgem2_es	knmi_racmo22t	r1i1p1	29.22	2560282	-0.35	-1.68	-2.03
rcp-8-5	ichec_ec_earth	mpi_csc_remo2009	r12i1p1	28.94	2462826	-0.28	-5.42	-5.70

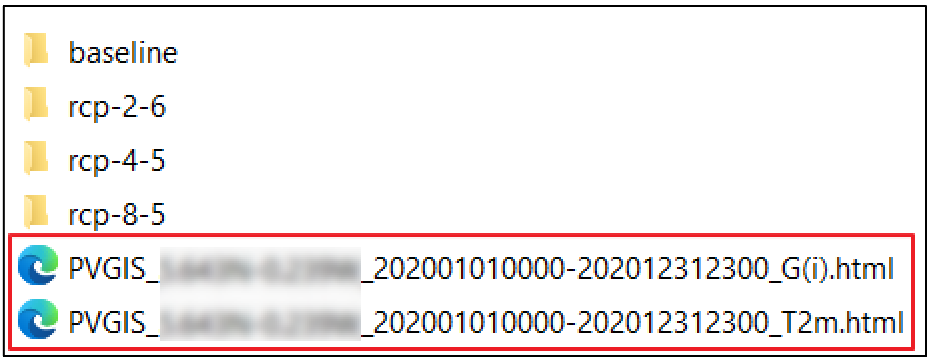
The proxy of the change in PV production (P_change (%)) is computed as follows:

1. The average annual temperature is computed when the radiation > 0 (T2m_annual_diurnal_mean)
2. It is computed the annual sum of the radiation (G(i)_annual_sum).
3. It is computed the change in production due to temperature, where an increase of 1°C can approximately decrease production by 0.40% (P_change_T2m (%)). The change in temperature is obtained by comparing the future model’s temperature with temperature in baseline scenario.

4. It is computed the change in production due to radiation, where an increase of 1% causes approximately the same increase in production (P_change_G(i) (%)). The change in radiation is obtained by comparing the model's radiation with baseline radiation.
5. Finally, both the change due to temperature and radiation are summed to get a final total production change (P_change (%)).
6. Models are arranged in descending order based on P_change (%) column.

A positive change will mean that the production will be higher than nowadays, while a negative one will mean the opposite. The model with the highest value of change will represent the best-case scenario for that horizon (2041-2060 in the example) and scenario (RCP8.5 in the example), while the one with the lowest will represent the worst-case scenario. The models in the middle of the ranking could be considered as the mean-case. To select the file that correspond to a given position in the ranking just check the gcm, rcm and ensemble member columns and construct the corresponding file name based on the standard naming explained above.

Finally, two interactive plots (one per variable) are available to interact with the hourly time series. It is possible to: query values, zoom in and out, check differences between experiments, etc.



In the following section, we will explain how to use and interpret all these results in combination with the LCOE Assessment Module.

2.3. Interaction between “Climate Projections Assessment Module” and “LCOE Assessment Module”

As explained, the Climate Projection Assessment Module was designed to work together with the LCOE Assessment Module. All the CSV files generated by the climate projection service are suitable to be used as inputs for the LCOE tool. Therefore, these CSVs can be ingested either as weather input data (section 2.1.2.2) or input data for the sensitivity analysis (section 2.1.4.2).

As was previously mentioned, currently the LCOE module uses the same target year to describe the weather through the whole lifetime of the plant. However, this approach does not consider the effect that climate change will have in that weather in the coming years. The climate projection helps to address this limitation.

2.3.1. Considering the effect of climate change for a given model

This chapter illustrates this concept through an example that focuses on a single model.

- GCM: ichec-ec-earth
- RCM: smhi-rca4
- Ensemble member: r12i1p1

To know the effect of future climate change based on this specific model, 9 files (3 emissions scenarios x 3 time horizons) are considered that correspond to that model (for the moment, the specific position of the model in the ranking is ignored):

CORDEX_[redacted]_20210101-20401231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-2-6_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-2-6_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-2-6_202001010000-202012312300.csv

CORDEX_[redacted]_20210101-20401231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-4-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-4-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-4-5_202001010000-202012312300.csv

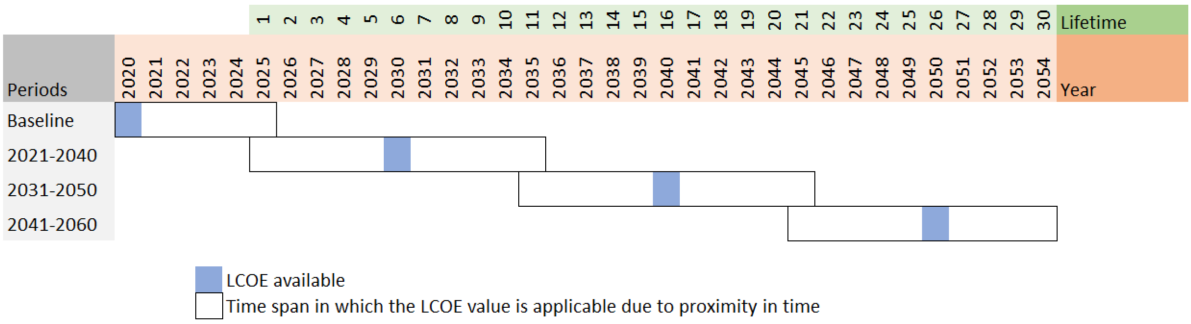
CORDEX_[redacted]_20210101-20401231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20310101-20501231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-8-5_202001010000-202012312300.csv
CORDEX_[redacted]_20410101-20601231_-_ichec-ec-earth_smhi-rca4_r12i1p1_rcp-8-5_202001010000-202012312300.csv

The first step is to compute the LCOE for each of the previous files. To do that, each CSV file is introduced iteratively in the LCOE tool through the weather input field (section 2.1.2.2). This way, 9 LCOE values are obtained: one per scenario and time horizon. It is important to remember that, in addition to these 9 values for future scenarios, baseline LCOE should also be computed. This baseline LCOE was originally obtained based on the CSV file that is directly downloaded from the PVGIS platform. In this example, the target year used to describe the baseline weather is 2020. Therefore, the available LCOE values for this example will be:

1. $LCOE_{baseline,\ 2020}$
2. $LCOE_{RCP2.6\ ,\ 2021\text{-}2040}$
3. $LCOE_{RCP2.6\ ,\ 2031\text{-}2050}$
4. $LCOE_{RCP2.6\ ,\ 2041\text{-}2060}$
5. $LCOE_{RCP4.5\ ,\ 2021\text{-}2040}$

6. $LCOE_{RCP4.5\ ,\ 2031\text{-}2050}$
7. $LCOE_{RCP4.5\ ,\ 2041\text{-}2060}$
8. $LCOE_{RCP8.5\ ,\ 2021\text{-}2040}$
9. $LCOE_{RCP8.5\ ,\ 2031\text{-}2050}$
10. $LCOE_{RCP8.5\ ,\ 2041\text{-}2060}$

In this example, it is simulated a power plant that will enter into operation in 2025 and has an expected lifetime of 30 years (until 2054). Consequently, the power plant would be affected by different climates during its lifetime. Therefore, to combine the LCOE of the different time horizons for each emissions scenario (RCP2.6, RCP4.5, RCP8.5), it is needed to apply a weighted average based on the years in which a given climate will be present during the lifetime of the plant:



Must be underlined that, although the time horizons are based on 20 years, the values of those years are used to extract the statistical distribution of the variables. Therefore, it is usually considered that the climate described by those years can be described as the climate of the central year (e.g. 2021-2040 = 2030). In the previous figure, four blue squares were defined: one for the target year (2020) and three for the central year of each future time horizon. Knowing that, the weight can be defined as the number of years in which a given climate is applicable considering the LCOE of the year that is closer. Thus, this weight can be used to get a final LCOE that will integrate the climate signal. The general equation to obtain the final LCOE for each emission scenario could be something like:

$$LCOE_i = \frac{w_{baseline,y} \cdot LCOE_{baseline,y} + w_{i,2021-2040} \cdot LCOE_{i,2021-2040} + w_{i,2031-2050} \cdot LCOE_{i,2031-2050} + w_{i,2041-2060} \cdot LCOE_{i,2041-2060}}{w_{baseline,y} + w_{i,2021-2040} + w_{i,2031-2050} + w_{i,2041-2060}}$$

Where *y* is the target year that describes the baseline climate, *i* is the emissions scenario (RCP2.6, RCP4.5 or RCP8.5) and *w* is the weight in number of years. In this example, the equation would be:

$$LCOE_i = \frac{1 \cdot LCOE_{baseline,2020} + 11 \cdot LCOE_{i,2021-2040} + 11 \cdot LCOE_{i,2031-2050} + 10 \cdot LCOE_{i,2041-2060}}{1 + 11 + 11 + 10}$$

Getting $LCOE_{RCP2.6}$, $LCOE_{RCP4.5}$ and $LCOE_{RCP8.5}$

2.3.2. Considering the effect of climate change for multiple models

Once it is known how to integrate climate change considering a single model, the same exercise can be repeated for different models to get a distribution and, hence, an uncertainty.

It is suggested to get three LCOE values for each scenario and time horizon: the worst-case, the mean-case, and the best-case. To do that, based on the ranking we mentioned in section 2.2.4, those models should be selected in each time horizon that represent the worst scenario (lowest value regarding change in production), mean scenario (model in the middle of the ranking) or best scenario (highest value regarding change in production). As the user may note this approach may lead to the selection of different models in each horizon.

Another option could be to generate a combined ranking based on the rankings of the three future time horizons. In that way, models that on average represent the worst-, mean-, and best-case scenario are obtained, so the same model is used in each case.

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