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Modelling of the Optimal Impact of Photovoltaic Technology on a Sustainable Energetic Mix as Function of the Climate Conditions

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Abstract: ***The current global trend towards decarbonized energy systems forces countries to encourage the inclusion of renewable energy. Among the main challenges, intermittent electricity production due to the fluctuation of the solar resource. In addition, the variability of costs associated with the availability of the local resource may limit its contribution toward the demand side. The trend of these possible medium-term limitations of PV energy production associated to the capacity of solar resources has been estimated. Across the OSeMOSYS open-source software tool, two optimizations have been modeled, one merely economic and the other including energy sustainability estimators. As main result, the medium-long term PV contribution appears as residual for cold and moderate climates with medial day-to-day irradiation of less than 3.2 Peak Solar Hours. In addition, a trend towards saturation 40% of the energy coverage for highly irradiated areas is observed. This effect, associated with the non-availability of resources at night, can be mitigated by incorporating accumulation technologies. The inclusion of energy sustainability criteria enhances previous considerations.***
Keywords: Solar Photovoltaic , Energetic Sustainable Transition, OSeMOSYS modelling

I. INTRODUCTION

In light of the 2015 Paris Agreement on Climate Change, resilience has brought global consensus on the need to embrace new strategies for energy production, distribution, and usage [1]. Likewise, the transition from fuel-based power generation to carbon-neutrality is the great global challenge and represents a point of no further progress in the pursuit of a viable climate and stands out as the key pillar of the Sustainable Development Goals (SDGs) [2].

Renewable energy (RE) sources have emerged as the most appealing options for achieving power sector decarbonization since they are clean, secure, and considered sustainable [3]. Global policy processes and market frameworks are intended to ensure widespread adoption of RE in global and national energy systems.

Among the various issues associated to this energy transition, those arising from technological reliability and sustainability are especially essential, since they imply wide variety of production to satisfy the economy's energy demands. The fundamental global policy concerns in the post-2015 era has been led by the expansion of wind and solar power plants [4]. A relevant challenge of these of technologies is their significant resource fluctuations. The electricity generation of an intermittent generation source is generally substantially lower than its potential output or installed capacity exhibiting marked fluctuations over relatively short periods of time. In the case of solar power plants, these fluctuations are explained by cyclical and seasonal factors that can be predicted (e.g., hours of sunlight). An alternative to alleviate the unwanted effects of intermittency is to incorporate the use of storage technologies that allow to soften the effects of these.

Despite its intermittency, solar technology presents a promising forecast in the global market in terms of costs and scalability [5] being currently considered economically competitive with respect to other conventional sources. Solar energy production costs have fallen by 90% between 2009 and 2020, according to U.S. investment bank Lazard. In 2022, electricity from large solar plants cost a global average of just $0.037/kWh. By comparison, electricity generation costs from new coal plants were three times higher, at $0.112/kWh, while natural gas cost $0.059, nuclear $0.163 and wind $0.04/kWh. However, its competitiveness rate depends on the availability of local resources and other associated climatic factors. This means that the difference in cost per kWh produced varies up to 40% depending on the solar plant radiation levels [2].

The identification of the most appropriate technology is important for guaranteeing significant incorporation of intermittent renewable energy resources as function the local resource in the power mix [3]. That is, through medium and long-term energy system planning studies, optimal technologies and associated capacity needed for achieving policy priorities can be identified.

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These kinds of assessment are undertaken over a long-time horizon and encompasses future demand expansion, technology, or policy agenda [3], [6]. Depending on some inputs (technical, economical, policy), they examine in each single stage with upgrades to existing capacity alongside the installation of new capacity, which may be in the form of generation units, electricity transmission and distribution lines, among others. Herefore, numerous flexible and open tools are now available to handle this kind of energy planning, each with a distinct methodology and numerical method, which is the case with Open-Source Energy Modeling System (OSeMOSYS). OSeMOSYS basis for economical optimization has been employed in a number of research, and a review of the literature revealed that authors such as [7]–[12] developed methodologies based on constraints, such as cost assessments, CO2 emissions activities, energy efficiency, and energy security, to mention few of. Indeed, economic optimization alone is insufficient for an adequate energy planning system. Other sustainability-related optimization criteria need to be introduced when analyzing different scenarios during the modeling of energy systems, and so far, few studies address this issue. As a matter of fact, the energetic sustainability indicators were integrated in OSeMOSYS as an extra cost [13]. This methodology employs the multicriteria approach by introducing the energy payback time (EPBT) the associated energetic sustainability indicator of several technology was used within an optimization of a set scenarios to evaluate the major effects. The well-known framework called Atlantis developed by M. Howells et al [14], is considered as case study. Although the Atlantis data is far from realistic, its use is interesting due to the various power generation technologies used in its modelling, including renewable and non-renewable.

The Capacity Factor (CF), which effectively examines how frequently a plant operates at full capacity, is one of the parameters utilized when energy modeling is occurred. This parameter is useful for expressing the radiation level of solar photovoltaic that varies between regions, for e.g., solar technologies have a Capacity Factor of zero at night, but during the day, it depends on the region irradiation level, thus the CF of a region with a long-time irradiance level will have a greater proportion of CF than a region with a shorter irradiation time.

Utilizing the methodology developed by [13], this paper assesses the effect of the solar resource on the desirable maximum limits in the percentage of contribution of solar energy to the electric energy vector. A set of scenarios is developed, in which in first the effect associated with the effect different PV CF is analysed, afterward scenario is built to evaluate the impact related to the energetic sustainability and then the resulting results are compared while accounting for the optimization estimators on economic parameters and introducing constraint. Although the current analysis is based on a fictional country, it has allowed us to confirm the strong dependence on cost-effectiveness of incorporating an intermittent energy source such as solar PV with the available resource as well as to assess the sustainability of energy mix planning.

II. METHODOLOGY

Developing a comprehensive energy transition pathway is a difficult endeavour which becomes even more complex when the incorporation sustainability criteria is envisaged. A wide variety of tools and approaches are accessible for this aim, such as OSEMOSYS, which enables informed decision-making by evaluating the medium-long term implications of pathway scenarios.

The ATLANTIS energetic mix instance of OSeMOSYS was employed in this paper to analyze how the implementation of sustainable development criteria affects the energetic mixing optimization. Aside from the energetic sustainability as an optimization constraint, the reliability of renewable technology, notably photovoltaic (PV), is also considered, and therefore a novel approach for estimating the solar Capacity Factor (CF) of any location on the globe is established.

Basically, Atlantis is a fictitious country featuring characteristics of both emerging and advanced countries that was created in MoMani, an OSeMOSYS interface, as an exercise for improvement and test control. The variables (technical and economic) used in Atlantis are not country specific and were derived from International Renewable Energy Agency papers and IEA-Energy Systems Analysis Program -Technology briefings (E01, E02, E03, E06, E10 and E11). Numerous scenarios associated to PV CF and energetic sustainability as an optimization constraint are thus developed and then analyzed from an economic and sustainability standpoint.

This section contains the energy modeling and optimization tool (OSeMOSYS). Similarly, the energetic sustainability indicator is discussed, followed by its introduction into OSeMOSYS as a constraint part of a sustainable optimization, and ultimately the PV CF estimation path is addressed.

A. OSeMOSYS Optimization Tool

Numerous models, mainly OSeMOSYS, have been developed to improve the design of energy supply networks by enhancing knowledge of the current and future interaction involving demand and supply, the environment, and the economy [11].

OSeMOSYS is referred to as a dynamic, bottom-up linear optimization model with a medium-to-long time horizon for integrated evaluation and energy planning [7], [15]. This energy design model tool quantifies the energy supply mix in terms of generation ability and supply, in addition to fulfilling demand for energy services throughout the year and at each stage of the case under investigation by optimizing the overall discounted costs on a global level [16], [17].

The merit variable to be optimized is the system total cost, which includes the initial investment, fixed costs, variable costs, and emission costs. The capital cost is the price for a new capacity expansion, while the fixed cost goes to maintaining the existing capacity. The variable cost is tied to each available capacity per technological unit [10].

Linear optimization is linked to diverse input variables that are related to technological constraints, economic realities, or environmental aims; as a result, it relies on a single decision-maker, flawless foresee, and competitive markets. The objective function constraint of demand coverage in OSeMOSYS is expressed by Equation (1).

$$TotCost_{y,t} = \sum_{y,t} (CapCost_{y,t} + FixCost_{y,t} + VarCost_{y,t} + EmissCost_{y,t}) \quad (1)$$

Where:

y: Year in the time frame.

t: Correlate to each technology under evaluation.

$TotCost_{y,t}$ [$]: Global cost of the system along the time interval under study.

$CapCost_{y,t}$ [$]: The associated annual Capital cost.

$FixCost_{y,t}$ [$]: Yearly Fixed cost per technology.

$VarCost_{y,t}$ [$]: Annual Variable/Production cost per technology.

$EmissCost_{y,t}$ [$]: The associated penalties for emissions.

After its initial release in 2011, various editions of OSeMOSYS have been developed to improve realism modeling and simulation circumstances such as time and relaxing optimization. These versions also include energy-related coding blocks like storage, short-term flexibility, and interconnections, among other. Nowadays, several analytical interfaces are in use, with MoManI being utilized for this aim.

B. *Energetic Sustainable Development Estimators*

When analyzing the sustainability of an energy system, three pillars of sustainability indicators are presently available to easily analyze the long-term sustainability and environmental performance [18], [19]. These metrics include the Energy Payback Time (EPBT), the most reliable, unbiased estimators to assess the energetic sustainability of a product, method, or endeavour. Expressed in year, EPBT is defined as the time needed for an energy producing system to produce the same amount of energy as was consumed to produce the complete system [20].

In fact, the integration of the energetic sustainability into OSeMOSYS, will follow the rationale behind the study developed by [13] in which EPBT is integrated into the optimization process via a correction function, with the main challenge being to convert an energetic variable into an economic cost weight. The core principle is that the energetic system must generate additional energy each year in order to recover the energy used during the implementation phase (cradle-cradle). Considering the excess production dispersed evenly across the year, a correction factor F_{EPBT} is defined for each technology as the ratio between the EPBT and the corresponding operational useful lifetime. The extra production will enhance the equivalent yearly Production Cost that is also the Variable Cost connected with the technology, while avoiding the deployment of extra energetic capacity. Equation (2) displays this additional variable, entitled Sustainable Production Cost.

$$SusProdCost_y = \sum_t ProdCost_{y,t} \times (1 + F_{EPBT,t}) \quad (2)$$

In accordance with the flexibility of OSeMOSYS, the EPBT is incorporated in MoManI, where its variable is exactly converted into an economic cost weight using the production cost function. The main goal is to provide more credit to technology that recovers the energy used during the deployment process quickly (cradle-cradle).

C. *Case Study: Atlantis Power System*

Utilizing the Atlantis energetic framework instance from OSeMOSYS, this paper investigates how the adoption of energetic sustainability influences energetic optimization in the MoManI interface [14], which has been designed as a paradigm for software validation and control.

Table 1: Data setting for the Reference Energy System

Parameter / Technologies	Fixed Cost (M$/PJ)	Capital Cost (M$/GW)	Variable Cost (M$/PJ)	Useful Life time (Year)	EPBT (Year)	F_{EPBT}
Natural Gas (NGSC)	44	2300	24.05	30	8.17	0.27
Diesel Generator (DSGC)	36	900	22.49	30	12.68	0.42
Integrated Gasification Coal (IGCC)	148	3700	11.58	35	12.93	0.36
Heavy oil (HFSC)	50	2300	30.23	35	29.33	0.84

The Atlantis energy framework consists of five power plants, each of which uses a different imported fuel type. Among the installations are a large hydroelectric plant, a single cycle steam turbine that uses heavy fuel oil, a single cycle steam turbine that uses natural gas, a diesel-fed gas turbine, and a coal-based integrated gasification combine cycle plant. Over the course of the modeling period, this system is being expanded in order to assess the viability of incorporating new technologies such as wind turbines (25% load factor), mini hydro power plants (less than 1 MW), concentrated solar power (CSP), grid-connected PV systems (commercial), rooftop PV systems (in residential areas), a nuclear power plant (light water reactor), and new combined cycle power plants powered by natural gas.

The Reference Energy System (RES) is a conceptual representation of the real energy system that is being modeled, and it displays the flow of energy horizontally from resources on the far left to final energy usage on the far right [21]. Resources, primary, secondary, tertiary, and final demand, which is broken down into several demand sectors, are the five key energy levels in the Atlantis scenario.

Most of the Atlantis default data are used, as described in the Momani Training Manual [14]. In order to provide a more realistic appearance, certain of the initial parameters that had a less than ideal configuration were reviewed. In fact, the current Atlantis parameters were developed using technical and economic inputs from the previous decade; however, in light of recent advancements and the quick adoption of renewable and even non-renewable technologies, some important parameters, such as the variables cost and emissions per unit of energy, have been updated.

Among the changed settings was the restriction of the large hydroelectric plant's maximum annual output to 2 PJ rather than the default unrestricted output. Additionally, because CSP, and PV roof technologies were disabled during the initial Atlantis modeling, these technologies are not covered in this paper.

Additionally, nuclear technology has consistently been at the centre of social debate and is hence seen as a non-proliferation technology, therefore, it is hard to measure its EPBT properly. While nuclear fuel efficiency is high, the EPBT only lasts around three years in terms of production. However, considering the implementation of the power plant and waste management, the most recent estimates show a realistic EPBT between 80 and 300 years. Which is why, nuclear energy production is not considered in our analysis.

The updated parameters can be used to examine the implications of energy sustainability, however they're not ideal until the instance being studied is unique to a real country. Table 1 provides a detailed description of all the incorporated revised parameter data for the Atlantis energy Modeling system.

D. Capacity Factor

The Capacity Factor (CF) of a technology in OSeMOSYS measures simply the net production, that is the ratio between the MWh actually generated in a period of time and the maximum (theoretical) MWh that could be generated with the installed capacity of the plant, as seen by the equation (4).

$$CFt = \frac{Production_t}{Nominal\ Energy\ Production} \quad (3)$$

Where:

Production $_t$: It is the Real Energy production during a specific time slice (t).

Nominal Energy Production: Is the maximal energetic production.

The capacity factor for intermittent technologies, hardly depends on the resource availability. For solar technology, a first order hypothesis is defined in which the Nominal Energy Production at STC (25°C, 1000 W/m2) is considered. In terms of Output

Production, it is hardly dependent on the irradiation level in Peak Sun Hours (PSH). A PSH is defined as one hour in which the intensity of solar irradiance (sunlight) reaches an average of 1,000 watts (W) of energy per square meter.
Therefore, the Solar Capacity Factor for a given time slice can be calculated as the ratio between the Peak Solar Hour (PSH) of the region and the number of the total irradiation's hours, equation (5). Fig. 1 shows the corresponding linear relation.

$$Solar\ CF(\%) = \frac{SPH}{Irr \times t} \times 100 \qquad (4)$$

Where:
SPH [Wh/m^2]: Is the Solar Irradiation hours.
Irr [W/m^2]: irradiation at the Stc; Irr = 1000 W/m^2.
t [h]: time slice length.

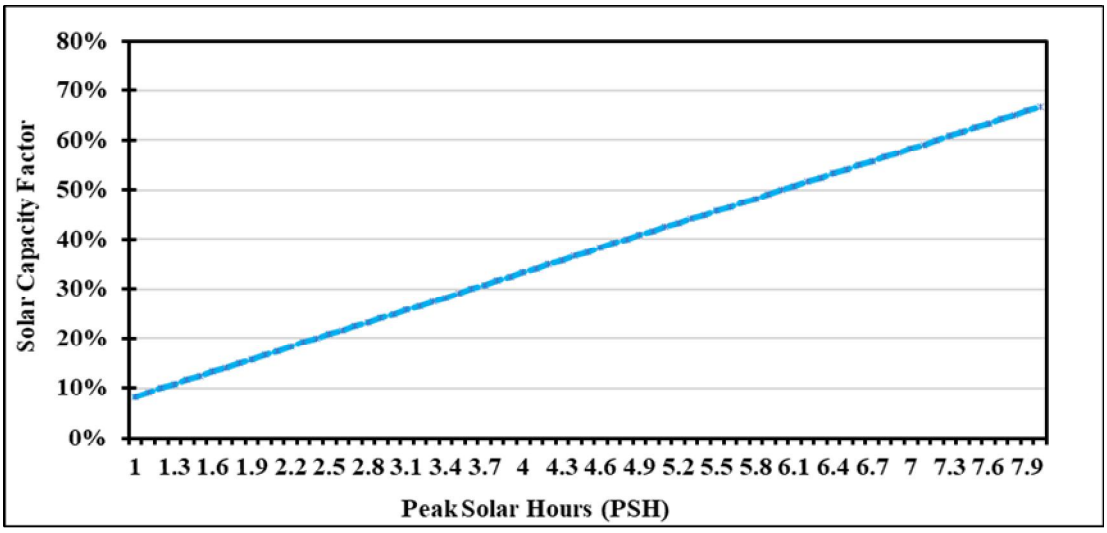


Fig 1. Solar technologies capacity factor for different irradiation levels

From the previous linear relationship has been constructed a first approximation of CF values using the Köppen climate classification [22] as shown in Fig 2. These values range from 10% to 70% and will serve as the basis for this study.

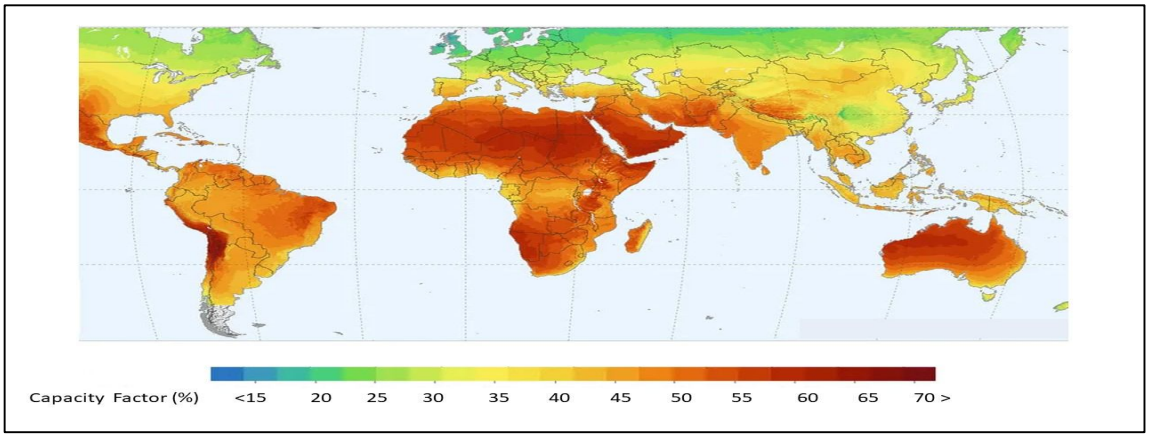


Fig 2. Global Solar CF in line with the Köppen-Geiger climate classification

III. RESULTS AND DISCUSSIONS

In response to the proposed objectives, two sets of working scenarios will be evaluated: those in which the energetic mix is optimized exclusively based on economic terms (Standard, as corresponds to the original OSeMOSYS) and others in which energy sustainability indicators (Energetic Sustainability, as EPBT indicator) are incorporated as an added constrain [13]. In each case, different sub scenarios scanning on CF in the range of 10 and 70% are evaluated.

Of the several output variables energy production and PV capacity were chosen as the most representative, each of which are global, that is, integrated into the temporal period under consideration (2024-2050). In terms of global energy production, the ones from PV, renewable technologies, and fossil sources have been divided into three categories. Only to further explore the impact of its CF, PV is taken separately of the renewable category.

To assess the impact of the radiation level on the optimal contribution of the PV technology, the percentage of demand covered will be examined for each of the scenarios. According to the Köppen-Geiger classification, and based on the obtained results, a first line of trend of the maximum levels of PV power to be installed will be proposed.

A. Standard Economic Optimization Scenario

Fig. 3 shows the optimal contribution of the different technologies included in the RES to the total coverage of demand for different values of solar resource characterized by the CF parameter. In this case, the objective function has been optimized exclusively in economic terms, as stated in the standard tool.

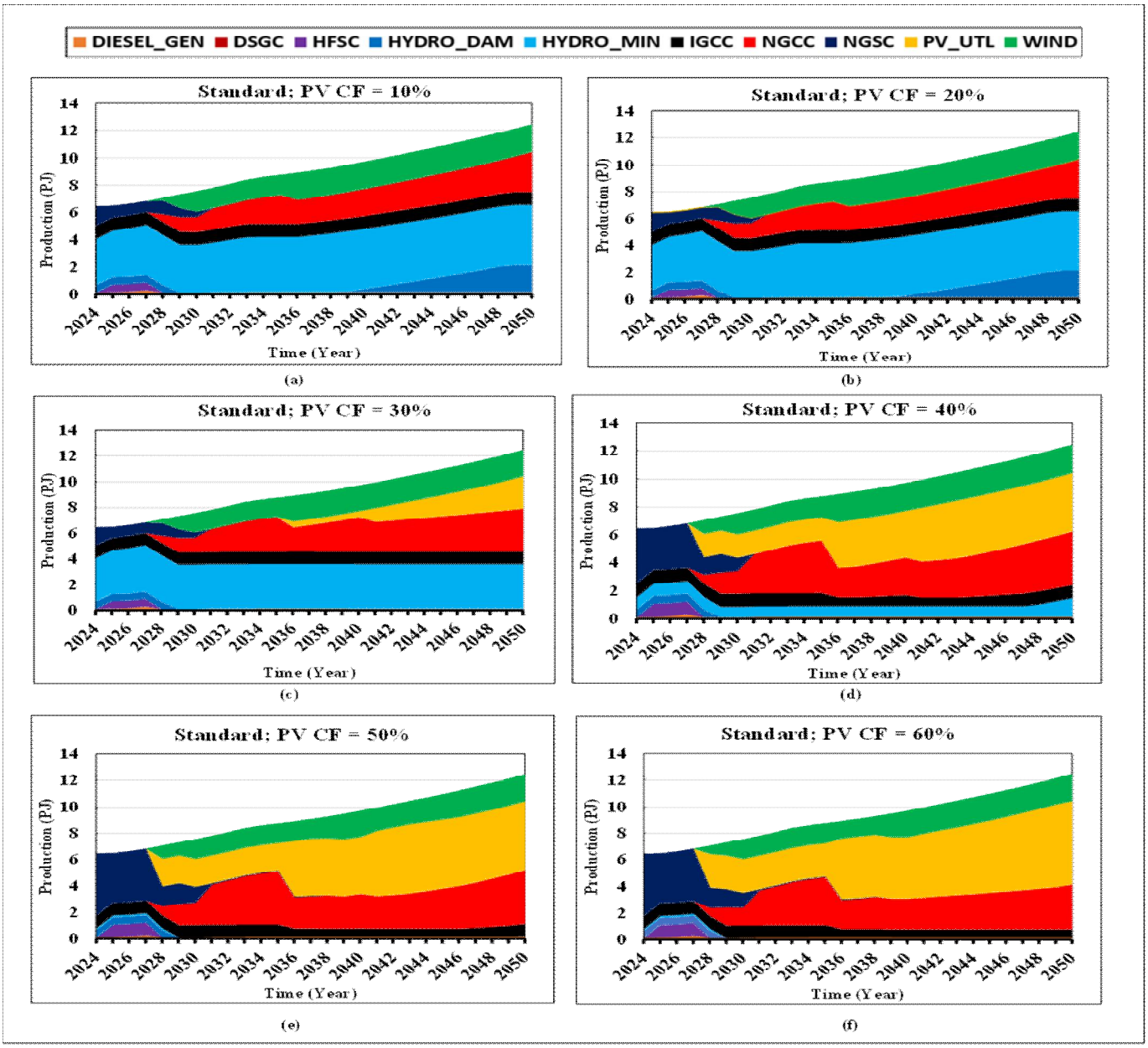


Fig. 3 Standard scenario. Yearly distribution of the energetic production differentiated by technologies. (a) CF=10%; (b CF=20%; (c) CF=30%; (d CF=40%; (e) CF=50%; (f) CF=60%

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It is important to highlight how the CF parameter as a measure of the availability of solar resources, is strongly sensitive to the contribution of technology in the energy mix. In fact, for climatic zones associated with CF less than 30%, that is PSH less than 3, economic optimization chooses not to disregard solar technology in favour of a mix that includes other technologies such as hydraulic, wind, gas and even coal. A trend towards a progressive increase in the energetic contribution of the PV component in the CF-range between 30% and 50%. This growth in terms of contribution to total demand is notable from CF = 30%, with a tendency towards a slowdown (plateau effect) for CF values above 50%. The saturation is associated with the availability of solar resources during the night hours which imposes a natural limitation. Disclosing a saturation effect from CF higher than 60% that corresponds to the most irradiated areas of the world.

To estimate numerically, energy contributions have been characterized into three categories: Solar, other renewable sources and fossil sources. The results, shown in Fig. 4, allow some result of interest to be extracted.

Accounting the uncertainty of the modelling tool, estimated at 5%, there is a limit of total participation of renewable energies (PV included) close to 60% that seems to show a slight decreasing trend with the increase in CF. There is also a natural compromise between the growth of PV component with decrease of the rest of renewable energies. It is also noteworthy the increase in fossil and nuclear energies that must be interpreted as the need to respond to the intermittency of the solar component.

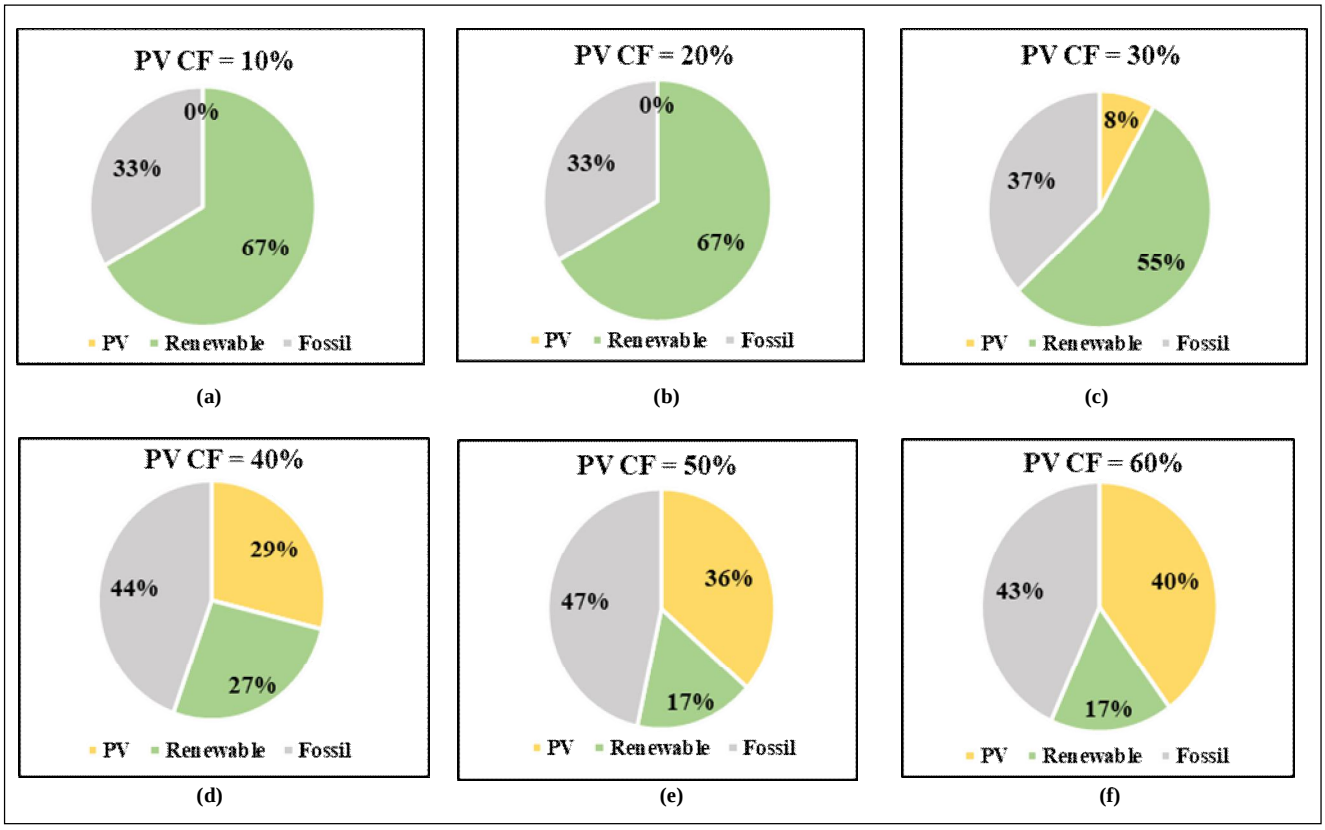


Fig. 4 Percentage of the energetic production of each defined category at the standard scenario; (a) PV CF=10%; (b) PV CF=20%; (c) PV CF=30%; (d) PV CF=40%; (e) PV CF=50%; (f) PV CF=60%.

Photovoltaic technology appears as competitive only when CF>=30% with an 8% contribution to the total mix, showing a linear growth up to a coverage of 36% for a CF of 50%. From for growth by the saturation effect already mentioned (see Fig. 4 c-d-e). In the same line, from Fig. 4-f it can be inferred that, always without including storage technologies, in no case can the contribution of solar energy to the coverage of energy demand be greater than 40%, leading the renewable sources for regions highly irradiated.

B. Optimization Scenario Including Energetic Sustainability Estimators

To evaluate the effect of the application of energy sustainability criteria in the process of optimizing the energy mix, Fig. 5 shows the energy contribution of each of the defined categories: solar, other renewable sources and fossil sources.

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As a general comment, the application of the convolution of economic and energy sustainability constraints, ensure a greater global contribution of renewable energies approaching 75% of total coverage while the fossil category reaches at least 25%. At the same time, there is no increase in the PV component, which implies a clear increase in the implementation of both wind and hydraulic energy. The share of renewable energy in the energetic mix has been declining due to the deployment of solar technology in scenarios where PV CF exceeds 30%. This fall can also be explained by the effect of incorporating the EPBT. Indeed, some renewable technologies, such as wind, have a higher F_{EPBT} than the fossil and photovoltaic categories which contributes to the renewable category dropping and an effective PV replacement.

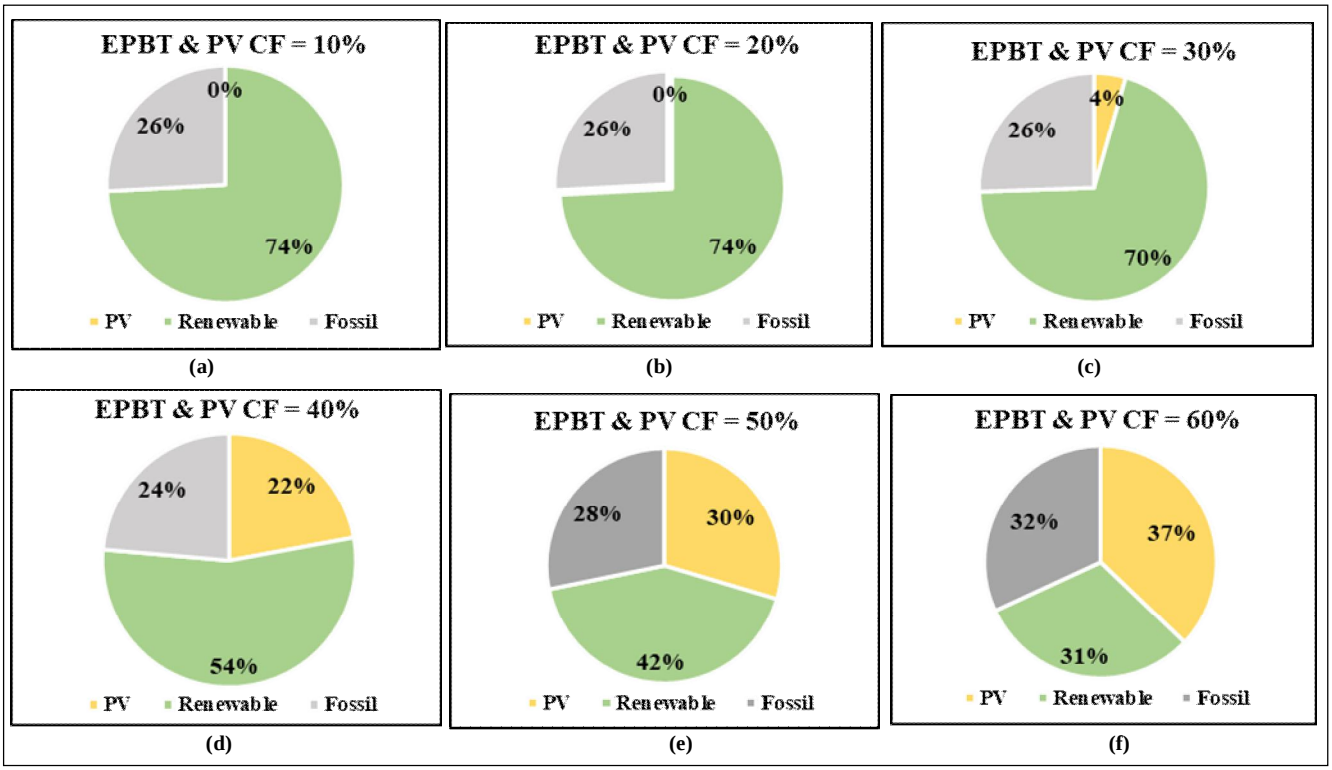


Fig. 5 Percentage of the energetic production of each defined category within the energetic sustainability application; (a) EPBT & PV CF=10%; (b) EPBT & PV CF=20%; (c) EPBT & PV CF=30%; (d) EPBT & PV CF=40%; (e) EPBT & PV CF=50%; (f) EPBT & PV CF=60%.

The essential outcome of including energetic sustainability within those analysed scenarios is that PV technology cannot be deemed sustainable, at least in terms of energetic payback time in regions with a lower PSH. So, a longer-term investment that is more sustainable would be in fossil and other renewable technology. However, PV technologies are more favourable and can be an optimal technology in terms of energetic sustainability if an area has an asset in considerations of an PSH and consequently a CF of more above 30%.

To have a better understanding of the impact of energetic sustainability, Table. 2 summarized the global capacity of PV required for each of the investigated scenarios. The effect of the CF may be seen here as well. For instance, if considering in the Standard optimisation the sub scenarios of 30% and 60% PV CF, its significant up to 40% in PV CF of 60% while only 8% is the PV contribution in mix in CF of 30% in terms of PV global production (see Fig. 4 for details). Yet, the needed capacity only increases by 10% for CF 60%.

Table 2. Global PV output capacity (GWh)

	CF=10%	CF=20%	CF=30%	CF=40%	CF=50%	CF=60%
Standard Scenario	0	0	5.56×10^{3}	1.99×10^{4}	2.51×10^{4}	2.75×10^{4}
Energetic Sustainability Scenario	0	0	3.07×10^{3}	1.52×10^{4}	2.04×10^{4}	2.56×10^{4}

As a result of the lower production efficiency induced by the CF in the lower radiation area, the PV capacity required is impressive, increasing the initial investment for a minimum output while generating a maximum production in the higher CF area. When energetic sustainability is applied, the impact is significant and inhibits PV expansion within lower irradiation, as seen in the sub scenario of 30% PV CF when total capacity is decreased to 44% for a significantly lower production.

C. Recommendations on Optimal Limits for PV Participation in the Energetic Demand Coverage:

All the results obtained have been based on a dependence on the CF parameter that represents the production capacity of photovoltaic solar energy. But the linear relationship of CF with local solar radiation should not be forgotten. Based on this correlation, the results acquired can be transferred to the different climatic characteristics so that we can make a first rude guide of the most appropriate areas so that solar technology can be considered as competitive. Based on the Köppen-Geiger climate classification, Fig. 6 illustrates the possible utility of the proposal, using the standard optimization scenario.

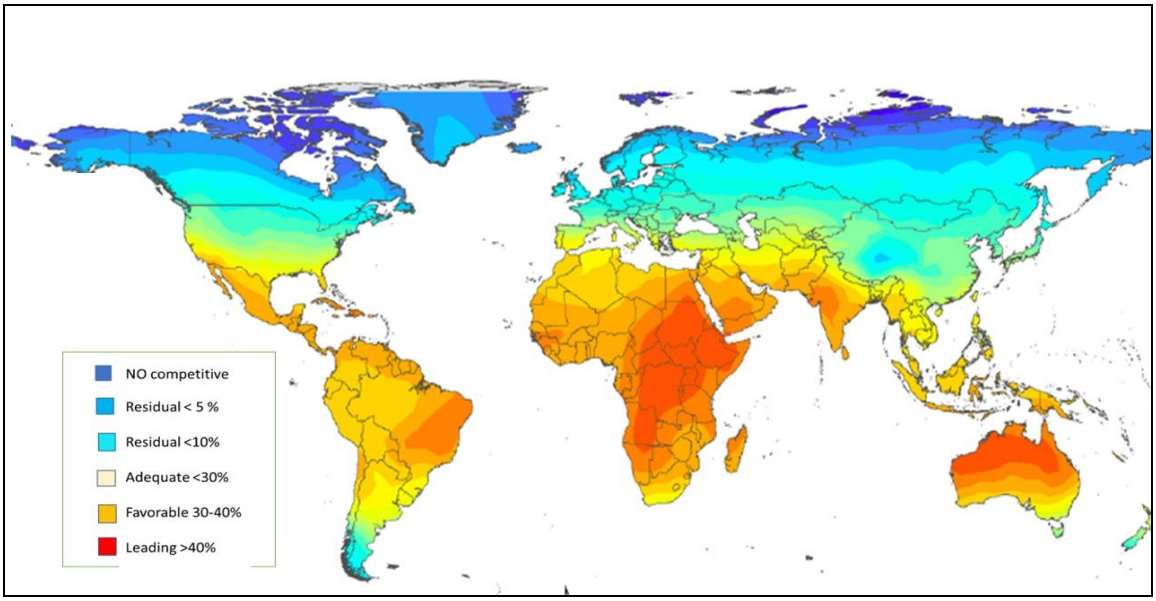


Fig. 6 General PV selection based on the Köppen climatic classification

In order to facilitate decision-making, five categories have been defined that qualitatively allow to establish the adequacy of the PV installation in the energy mix (see details in Table. 3).

Table 3. Competitiveness PV categories characterization.

Competitiveness PV level categories	Mean daily radiation level (PSH)	PV contribution to demand coverage (%)
No competitive	< 2.5	0
Residual	[2.5 , 3]	[5 , 10]
Adequate	[3, 4]	[20, 30]
Favorable	[3,5, 5]	[30, 40]
Leading	>5	±40

The competitiveness of photovoltaics is hardly inhibited both in economic and sustainability terms for areas weakly irradiated (SPH<3) In these areas, which normally presents a high seasonality, the contribution of technology should be considered residual although surely interesting for residential purpose.

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Finally, in the most irradiated areas of the planet (SPH>5), photovoltaic technology can lead the energy mix with 40% of the total coverage of demand. This limit, induced by the intermittency of production, can be broken with the incorporation of adequate storage systems.

IV. CONCLUSIONS

Attending the post-2015 era energetic global policy is leaded by the expansion of wind and solar power plants, the main challenge to face is their significant resource fluctuations. Despite its intermittency, solar technology presents a promising forecast in the global market in terms of costs and scalability being currently considered economically competitive with respect to other conventional sources. However, its competitiveness rate depends on the availability of local resources and other associated climatic factors incorporating a new uncertainty because difference in cost per kWh produced varies up to 40% depending on the solar plant radiation levels.

To evaluate the impact of PV on a sustainable energetic mix as function of the climatic conditions through medium and long-term energy system planning an energy modelling, based on the Open-Source OSeMOSYS optimization tool has been designed and evaluated. As case of study, the Atlantis fictitious country has been considered. Although the Atlantis data is far from realistic, its use is interesting due to the various power generation technologies used in its modelling, including renewable and non-renewable. The Capacity Factor (CF), which effectively examines the operative efficiency of a solar plant, directly related with the local radiation level has been used as variable of merit.

Appling the proposed methodology, the effect of the solar resource on the desirable maximum limits in the percentage of contribution of solar energy to the electric energy vector is assessed. A set of scenarios is developed, in which in first the effect associated with the effect different PV CF is analysed, afterward scenario is built to evaluate the impact related to the energetic sustainability and then the resulting results are compared while accounting for the optimization estimators on economic parameters and introducing constraint.

As main results, the pure economic optimization shows how climatic zones associated with CF less than 30%, the economic optimization chooses not to disregard solar technology in favour of a mix that includes other technologies such as hydraulic, wind, gas and even coal. A trend towards a progressive increase in the energetic contribution of the PV component in the CF-range between 30% and 50%, This growth in terms of contribution to total demand is notable from CF = 30%, with a tendency towards a slowdown (plateau effect) for Cf values above 50%. The saturation is associated with the availability of solar resources during the night hours which imposes a natural limitation. disclosing a saturation effect from CF higher than 60% that corresponds to the most irradiated areas of the world.

Similar results are obtained when sustainability-related criteria are included into the optimization process, being the most interesting difference, a greater global contribution of renewable energies approaching 75% of total coverage while the fossil category reaches at least 25%. At the same time, there is no increase in the PV component, which implies a clear increase in the implementation of both wind and hydraulic energy. The share of renewable energy in the energetic mix has been declining due to the deployment of solar technology in scenarios where PV CF exceeds 30%.

Finally, based on the linear correlation between CF and mean daily irradiation level (PSH), the results acquired and based on the Köppen-Geiger climate classification, has been transferred to a first rude guide word map. This tool allows a first classification of suitability of the PV technology divided into five categories attending the limits of maximum desirable solar contribution in the total energy mix. The competitiveness of photovoltaics is hardly inhibited both in economic and sustainability terms for areas weakly irradiated (SPH<3). In these areas, which normally presents a high seasonality, the contribution of technology should be considered residual although surely interesting for residential purpose. Finally, in the most irradiated areas of the planet (SPH>5), photovoltaic technology can lead the energy mix with 40% of the total coverage of demand. This limit, induced by the intermittency of production, can be broken with the incorporation of adequate storage systems.

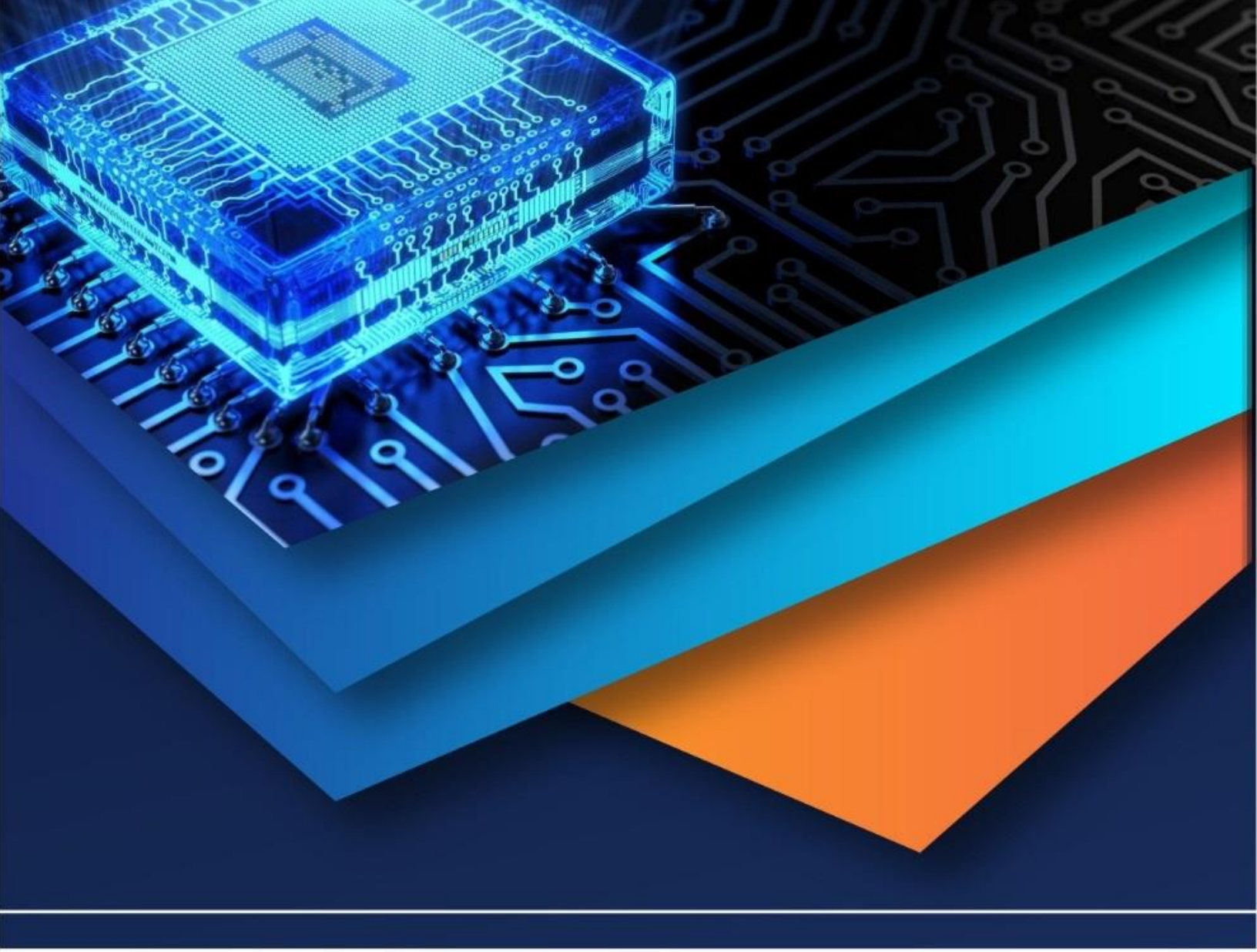
Although the current analysis is based on a fictional country, it has allowed us to confirm the strong dependence on cost-effectiveness of incorporating an intermittent energy source such as solar PV with the available resource as well as to assess the sustainability of energy mix planning.

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