# Environmental and economic assessment of hybrid solar-wind farms as a sustainable model for the development of solar energy in Uruguay

**Emilio Deagosto Vinas**

**Supervisor:** Sharon Joyce

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## Declaration

I declare that this assignment is my own work and that I have correctly acknowledged the work of others. This assignment is in accordance with University and School guidance on good academic conduct (and how to avoid plagiarism and other assessment irregularities).

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## Executive Summary

Uruguay has been expanding its energy sector with a strong emphasis in renewable and indigenous sources in the last decade. This expansion has been particularly focussed on the electricity sector and mainly driven by wind power and biomass. Currently, the Uruguayan Government is evaluating alternatives to further expand the electricity sector and it is especially interested in solar photovoltaic energy, since the solar resource presents an excellent complementarity with the wind resource. Furthermore, developing solar energy will allow the country to continue diversifying its energy mix based on renewable sources.

However, the cost of the technology is still a relevant issue that prevent it from being fully developed in Uruguay and therefore, alternatives must be evaluated to make it economically viable. In this context, the hybrid wind-solar power plant model may be an effective strategy to bring costs down by taking advantage of the existing infrastructure and operating two power plants in the same site. In addition, the hybrid model also has environmental benefits.

In this study, the hybrid model was assessed from an economic and environmental view, considering general matters and specific features of a case study in Uruguay. The economic evaluation was conducted following traditional methodologies of project evaluation (LC, CBR, PP, IRR and LCOE), using the most updated data and consulting experience professionals in the renewable energy field. The environmental assessment was carried out by considering the environmental regulatory framework and following the *EU Guidance on EIA*.

The hybrid configuration may reduce the investment costs of solar photovoltaic projects by 15.7% and O&M costs by 23% in the range of 5 MW to 25 MW capacity in Uruguay. Due to these cost reductions and despite some technical constraints, hybrid projects are more profitable than the conventional option (power plant installed independently) under the conditions and assumptions of this study, particularly for small to medium scale power plants.

The total investment cost of a conventional project must decrease between 13.5% to 20.0% if it is to achieve the same economic outcomes as the hybrid configuration under the same conditions. Likewise, the energy prices must increase between 10.7% to 15.7% to get the same results. Furthermore, only hybrid projects would be profitable at energy prices between 70 USD/MWh to 75 USD/MWh, which would likely be the price range if a call for projects would be made presently.

Regarding environmental matters, solar photovoltaic projects do not present critical issues in general terms. Moreover, the hybrid configuration may provide additional benefits, such as avoiding the construction of the transmission lines and minimising other intrinsic impacts.

Overall, the hybrid model may represent an effective strategy to boost the solar photovoltaic technology in Uruguay. It may be the key to accelerate the introduction of this technology, which would allow to avoid or delay the installation of thermal back-up and energy storage systems. Furthermore, it would contribute to continue diversifying the energy mix through indigenous and renewable sources, further expanding the energy sector in a sustainable way.

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## Acronyms and abbreviations

| | |
|---|---|
| AAO | *Autorización Ambiental de Operación* |
| AAP | *Autorización Ambiental Previa* |
| AC | Alternative Current |
| ADME | *Administración del Mercado Eléctrico* |
| ARENA | Australian Renewable Energy Agency |
| BEN | *Balance Energético Nacional* |
| CBR | Cost Benefit Ratio |
| CCF | Cumulative Cash Flow |
| CER | Certificate of Emission Reduction |
| DC | Direct Current |
| DINAMA | *Dirección Nacional de Medio Ambiente* |
| DNE | *Dirección Nacional de Energía* |
| EBITA | Earnings before interest, taxes, and amortization |
| FING-UdelaR | *Facultad de Ingeniería de la Universidad de la República, Uruguay* |
| GHG | Greenhouse gases |
| IPCC | Intergovernmental Panel on Climate Change |
| IRAE | *Impuesto a la Renta de las Actividades Económicas* |
| IRENA | International Renewable Energy Agency |
| IRR | Internal Rate of Return |
| LC | Lifetime Cost |
| LCOE | Levelized Cost of Energy |
| LES | *Laboratorio de Energía Solar* |
| MIEM | *Ministerio de Industria, Energy y Minería* |
| O&M | Operation and Maintenance |
| PP | Payback Period |
| PPA | Power Purchase Agreement |
| SimSEE | *Simulador de Sistemas de Energía Eléctrica* |
| UTE | *Administración Nacional de Usinas y Transmisiones del Estado* |

# 1 Introduction

Uruguay has been historically dependent on fossil fuels and hydroelectric power to meet its energy demands, which made it highly vulnerable to fluctuations in international fuel prices and weather conditions. Furthermore, being a small country with no proven fossil-fuel reserves meant that none of these factors were under its control.

However, in the last decade it has taken a truly energy revolution forward. Following the definition of the *Energy Policy 2005-2030*, it has strongly developed its energy sector based on indigenous and renewable sources. The policies implemented have led Uruguay to increase its energy independence and sovereignty, and the results achieved have led it to be worldwide recognised as a model for the sustainable development of the energy sector.

In recent years, renewable energies have covered more than 50% of its primary energy demand and they have accounted for over 90% of its electricity production. The expansion of these technologies has been particularly significant since 2014, and it has been mainly driven by the growth of wind power and biomass.

Currently, the Uruguayan Government is evaluating different strategies to further expand the energy sector. In this context, the excellent complementarity between the wind and the solar resources could play a key role in developing the solar photovoltaic technology, contributing to continue boosting indigenous and renewable sources, as well as diversifying the energy mix. In addition, it could also help to avoid or retard the installation of thermal back-up and energy storage systems.

Nevertheless, the cost of the solar photovoltaic technology has been an important issue and has prevented it from been fully developed in Uruguay. In 2015, the first large-scale solar power plant entered operation and even though some others have been installed ever since, the share of this technology in the energy mix is still incipient. Thus, alternatives must be sought to bring down the costs and facilitate its expansion in the country.

In this context, the development of hybrid wind-solar power plants may be an effective strategy to accelerate the introduction of the solar photovoltaic technology at large scales. The concept of co-locating power plants is being explored in different countries, and as a result, important benefits have been reported. Particularly, Australia and India have made considerable progress in this field, studying the potential of this power plant configuration, having developed projects and starting to introduce regulations.

In terms of the benefits of such a power plant configuration, it has been reported that capital cost savings could be up to 13%, while operational cost savings could be up to 16%. However, the benefits are not only economic, but also environmental. Optimising the existing infrastructure may allow avoiding further construction of substations and transmission lines, which are usually built up in areas of high natural value.

In this study, the potential of the hybrid configuration for contributing to the sustainable development of the solar photovoltaic technology in Uruguay is explored. An economic and environmental assessment is conducted considering political, economic, social, technical and environmental factors. Likewise, a case study is evaluated taking account of the current situation of the energy sector, analysing the latest available data and consulting experience professionals in the energy and environmental fields.

## *1.1 Objectives*

The main objective is to evaluate the economic and environmental benefits of the hybrid wind-solar farm model in the development of solar photovoltaic energy in Uruguay.

This objective consists of two major specific goals. Firstly, this study intends to evaluate the economic aspects of the hybrid configuration in Uruguay, particularly by analysing the installation of a solar photovoltaic power plant adjacent to an existing wind farm. Secondly, it aims at assessing the environmental matters of this type of power plant in the framework of the Uruguayan environmental regulations.

## *1.2 Scope*

This study addresses the economic and environmental aspects of a solar photovoltaic power plant installed adjacent to an existing wind farm in Uruguay, considering general matters and specific features of a case study (*Pampa* wind farm).

The scope could be defined from the two major specific goals, and it consists mainly on the following items:

- Examination of the main characteristics of the Uruguayan energy sector and its perspectives for the short, medium and long terms.
- Investigation of the complementarity of the wind and solar resources nationwide.
- Review of international experiences on hybrid power plants and environmental matters related to solar photovoltaic projects.
- Review of the Uruguayan environmental regulatory framework.
- Evaluation of the location for the case study.
- Evaluation of technical alternatives for using the existing infrastructure in hybrid farms, considering potential operational constraints.
- Analysis of project costs and energy costs of hybrid and non-hybrid configurations.
- Evaluation of the economic outcomes of installing a solar photovoltaic power plant adjacent to an existing wind farm in the location selected.
- Environmental impact assessment of a hybrid power plant, considering the regulatory framework and the environmental matters of solar photovoltaic developments.

# 2 Literature review

## 2.1 Uruguay

### 2.1.1 Overview

Uruguay is located in the southeast of South America, at the mouth of the *Río de la Plata* river into the Atlantic Ocean, bordering with Argentina on the west and Brazil on the north and northeast. It covers a surface area of 176,215 km$^2$ [1], which makes it the second smallest country in South America after Surinam [2]. The country is entirely placed within the sub-tropical zone, between latitude -30°06’ and -34°58’ and longitude -53°11’ and -58°26’ [1]. The location is shown in Figure 2—1.

**Figure 2—1 Location of Uruguay**

Uruguay has a population of 3,286,314 people, with almost half of it (1,319,108) living in the capital city, Montevideo [3]. It has a very low population density with 18.6 inhabitants per square kilometre. Furthermore, if Montevideo (530 km$^2$, 0.3% of Uruguay surface [4]) is not considered, this figure decreases to only 11.2 inhabitants per square kilometre. In terms of distribution, rural population represents merely 5.3% of the total [3].

Uruguay is recognised for having achieved high levels of economic and social development due to its high per capita income, low level of poverty and absence of indigence. It is considered one of the most egalitarian societies in Latin America and it usually ranks among the highest in well-being and human development indexes within the region. The country also stands out for its institutional stability and low level of corruption, and it has been recognised by The World Bank for its achievements in ensuring global access to basic services, including electricity [5].

In the last decade, Uruguayan economy showed an annual average growth rate of 4.8% [5], reaching a GDP per capita of USD 15,573 in 2015, the highest in South America [6]. In terms of employment, the country reached its historically low unemployment level in 2014, 6.6%, which increased to 8.6% in July 2016 following a process of economic slowdown [5].

### *2.1.2 History of the energy sector in Uruguay*

In the 19th century, wood was the primary fuel for the Uruguayan agricultural-based economy, and it still represented more than two thirds of the energy consumed by the beginning of the 20th century. After World War I, fossil fuels largely replaced it, and until 1945 the energy demand was met only through fossil fuels and informal use of wood. In 1945, it entered operation the first hydroelectric power plant, *Rincón del Bonete* [7], which initiated a long tradition of hydroelectric power exploitation in the country.

Since the second half of the 20th century, oil derivatives (mainly), hydroelectric power and wood represented the exclusive energy sources in Uruguay [7]. Towards the end of the century, hydroelectric power became increasingly important with the installation of three additional power plants, one of them shared with Argentina over the *Uruguay* river.

When referring to renewable energy sources in Uruguay, they are usually classified into conventional (large hydroelectric power) and non-conventional (solar, wind, biomass and biofuels, small-scale hydroelectric power, geothermal, wave and tidal). This fact is due to the long-established tradition of exploiting hydroelectric power for electricity generation.

In terms of electricity, fossil-fuels and hydroelectric power remained the exclusive sources until 2004, when electricity started to be generated from non-conventional renewable sources. Nevertheless, they only began to share a significant part of the energy mix since 2007 [8].

## ***2.2 Energy Policy 2005–2030***

Before 2005, the energy sector went through years of underinvestment and lack of planning. In fact, it was not until 2008 that Uruguay defined an energy strategy, which was the result of two-year discussions. The final document, the *Energy Policy 2005–2030*, was approved in 2008, and in 2010 it received the endorsement of all the political sectors represented in the legislative body [9]. The latter was fundamental, since the energy strategy became a state policy and should go beyond changes in the government.

The *Energy Policy 2005–2030* is a comprehensive plan that establishes the main guidelines for the sustainable development of the energy sector in Uruguay, with a long-term view. Its objective is to meet the national energy demand, in an affordable way, while contributing to the national competitiveness. It is aimed at promoting efficient and responsible use of energy and ensuring the energy independency within a framework of regional integrity, through environmental and economic sustainable policies. It also aims at contributing to develop national productive capacities and to promote social integration [10].

This policy is mainly focused on diversifying the energy mix through indigenous and renewable sources, reducing fossil-fuel dependency and promoting energy efficiency. For that purpose, the document established strategic guidelines, short, middle and long-term goals, and action lines. While the strategic guidelines and the goals should remain unchanged, the action lines are updated regularly following continuous analysis of the energy situation at national, regional and global levels.

### *2.2.1 Strategic guidelines*

The strategic guidelines were classified into four central categories, namely institutional issues, energy supply, energy demand and social aspects. The main outcomes of each area are summarised in the following items, particularly those related with the development of renewable sources.

#### 2.2.1.1 Institutional issues

- The Executive Power, through the *Dirección Nacional de Energía* (hereafter DNE) of the *Ministerio de Industria, Energía y Minería* (hereafter MIEM), is responsible for formulating and implementing the energy policy, introducing regulations and coordinating the public and private actors.
- The government-owned energy companies are essential to implement the policies, and they must count on funding to invest in infrastructure and human capital.
- Private sector participates according to the guidelines and regulations set by the Executive Power. Their actions should contribute to strengthen national capacities.
- Regulatory frameworks for the energy sector and its sub-sectors must be comprehensive, clear and stable.
- There must be funding available to promote research, development and innovation in the energy sector, as well as mechanisms to foster investments and development of national capacities.

#### 2.2.1.2 Energy supply

- The main objective in terms of the supply is to diversify the energy mix, reducing oil dependency and enhancing indigenous and renewable sources. In this context, the strategy emphasised the importance of exploiting renewable sources that can compete at market prices (wind, biomass, solar thermal, small-scale hydroelectric and biofuels).
- Regular infrastructure upgrading is necessary to strengthen the energy system. Likewise, it is important to enhance regional and international energy integration (eg interconnection with bordering countries and energy exchange agreements).

- Within the electricity sector, the introduction of renewable sources must be strategically scheduled and supported by analyses and promotion policies. Likewise, the expansion of the transmission and distribution networks must consider the increasing demand and the expected distributed generation.
- Microgeneration must be promoted at all levels, both for electricity and heating.
- An active technological prospecting is essential to be up-to-date and prepared to incorporate new and emergent technologies into the energy mix.

When the document was approved in 2008, solar photovoltaics was identified as an emergent technology. In fact, from the technologies identified as new or emergent at that moment, it was the only one which has been developed up to 2016. The other technologies were biofuels from second and third generation, hydrogen, concentrated solar power, wave and tidal.

#### 2.2.1.3 Energy demand

- The main objective in terms of demand is to promote energy efficiency at all levels (ie industry, construction, transport, agriculture and households), without reducing production and comfort levels.
- Demand-side measures must promote cultural changes related to consumption patterns. The government is responsible for driving that changes through the formal education system and other dissemination and information campaigns. It should also lead by example the transition into a more efficient use of the energy.
- Regulatory frameworks and taxation must promote energy efficiency.
- There must be funding to introduce necessary technological upgrading both at residential and industrial levels.

#### 2.2.1.4 Social aspects

- The government must ensure adequate, affordable and safe access to energy for all social sectors. The energy policy should be an instrument to promote social integration and support democracy, and must be aligned with social policies.
- Universal access to energy is a high priority of the energy policy, which must take account of the needs and context of each household.

### *2.2.2 Goals*

The goals of the *Energy Policy 2005–2030* were defined according to the strategic guidelines and they were classified into short-term, middle-term and long-term. The most relevant goals, particularly those related to renewable energy development, are shown in Table 2—1.

**Table 2—1 Main goals of the *Energy Policy 2005–2030***

| Period | Goals |
|---|---|
| Short-term (2015) | 50% of total primary energy mix from indigenous, renewable sources.<br>15% of electricity generation from non-conventional renewable sources.<br>30% of industrial and residential waste are used to produce energy.<br>100% electrification in the country (universal access to energy). |
| Middle-term (2020) | Optimum share of renewable sources in the energy mix (wind, biomass, solar thermal energy and biofuels).<br>Optimum use of waste for energy generation.<br>There have been developed pilot projects for new and emergent sources.<br>20% decrease in the use of energy in comparison with trend scenario. |
| Long-term (2030) | Uruguayan energy system is model at a global level.<br>USD 10 billion savings from replacement of energy sources and efficiency.<br>Optimum regional energy integration (particularly through interconnections with Argentina, Brazil and Paraguay). |

*Source: Deagosto, 2017* [11].

## 2.3 *Current situation of the energy sector*

### 2.3.1 *Primary energy supply*

Almost a decade after the approval of the *Energy Policy 2005–2030*, and having passed the short-term period defined (2015), it becomes useful to make a review of the energy sector situation in Uruguay. Nonetheless, any attempt to obtain a snapshot of the current situation will become out of date within a short period, since this sector has been evolving extremely fast in recent years.

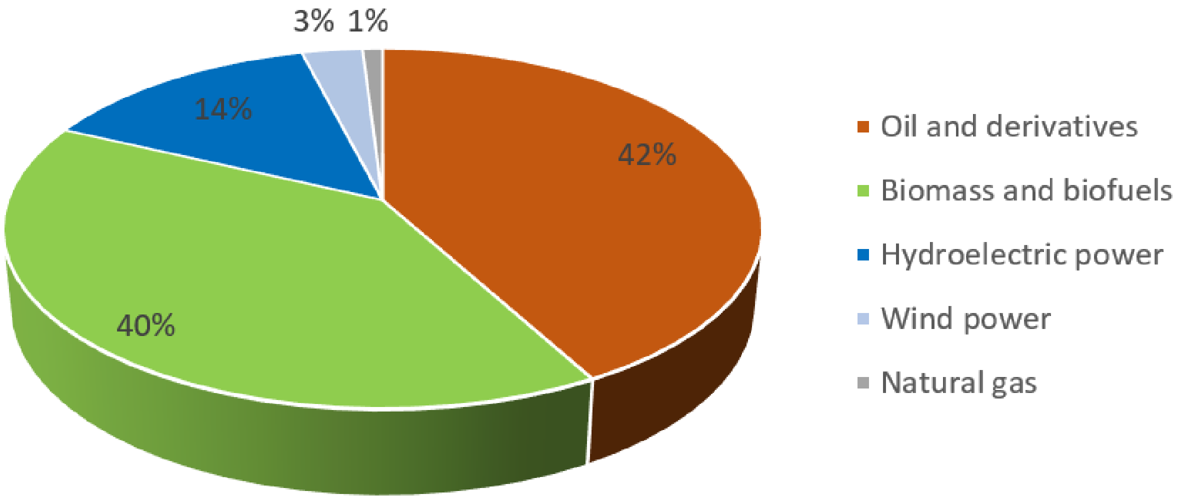
The DNE publishes the National Energy Balance (hereafter BEN) every year with all the relevant data of the energy sector in Uruguay. The last BEN was published in 2015, but there are some data available for 2016 from both the DNE and the government-owned electricity company *Administración Nacional de Usinas y Transmisiones Eléctricas* (hereafter UTE).

According to the last BEN, renewables accounted for 57% of the total primary energy supply mix in 2015, where biomass and biofuels accounted for 40%, hydroelectric power 14%, wind power 3% and other sources 1%, including solar energy.

The fossil-fuel share (43%) was comprised by 42% oil and derivatives and only 1% natural gas [12]. Figure 2—2 presents the 2015 primary energy supply mix classified per source.

The share of renewable energy in 2015 largely overcame the 50% goal set in the *Energy Policy 2005–2030*. Furthermore, in 2014 Uruguay had already overcome that milestone with 54% of total primary energy supply from renewable sources.

**Figure 2—2 Primary energy supply per source - 2015**



Note: Solar photovoltaic power is not represented due to its small share in the mix (below 1%).

*Source: DNE* [12].

When considering the renewable energy share of the global final energy consumption, estimated in 19.2% in 2014 [13], the figures achieve by Uruguay in recent years become more impressive. The latter has led it to be recognised worldwide as an example of sustainable energy development.

The Renewable Energy Policy Network for the 21st Century ranked Uruguay first within the countries with highest rate of GDP invested in renewable energy in the world in 2012 [14], with about 3% [15]. Likewise, it was the fourth country in Latin America in attracting absolute amount of investment in 2015, with 1.1 billion dollars [16].

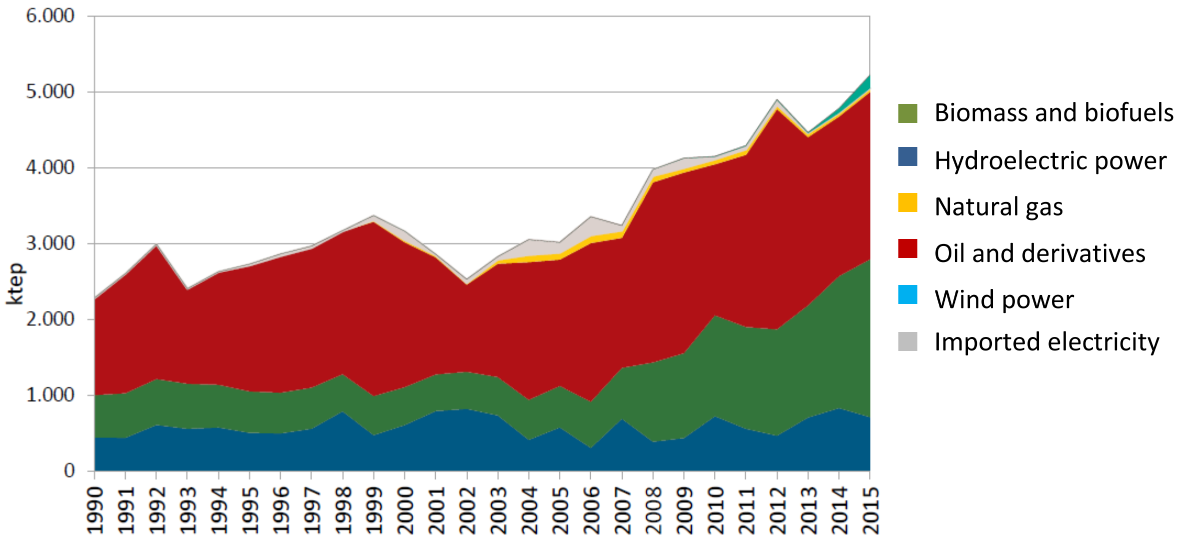
It is also interesting to analyse how the primary energy supply mix has evolved in recent years. Its evolution between 2011 and 2015 is presented in Table 2—2, while a graphic representation of the last 25 years is shown in Figure 2—3.

**Table 2—2 Evolution of the primary energy supply 2011 - 2015**

| Source | 2011[a] | 2012[b] | 2013[c] | 2014[d] | 2015[e] |
|---|---|---|---|---|---|
| Oil and derivatives | 53% | 59% | 50% | 44% | 42% |
| Biomass and biofuels | 31% | 29% | 33% | 36% | 40% |
| Hydroelectric power | 13% | 10% | 16% | 17% | 14% |
| Natural gas | 2% | 1% | 1% | 1% | 1% |
| Wind power | 0.2% | 0.2% | 0.3% | 1% | 3% |
| Imported electricity | 1% | 1% | 0% | 0% | 0% |
| *Total from renewables* | *44%* | *39%* | *49%* | *54%* | *57%* |

*Source:* [a]*DNE* [17]; [b]*DNE* [18]; [c]*DNE* [15]; [d]*DNE* [19]; [e]*DNE* [12].

**Figure 2—3 Evolution of the primary energy supply 1990 - 2015**

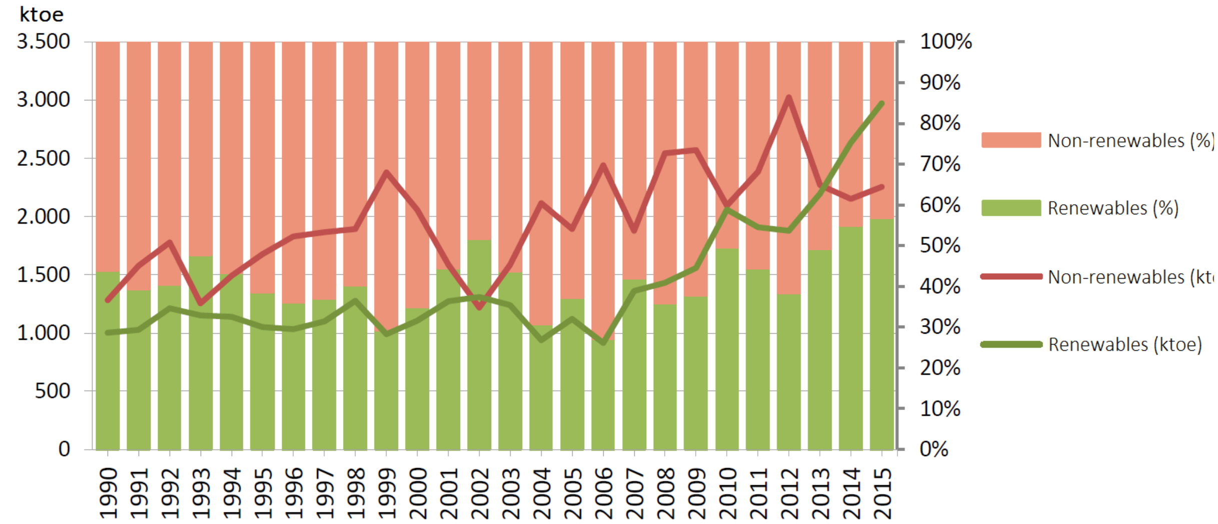


*Source: DNE* [12].

As can be seen in Figure 2—3, renewables have been significantly increasing since 2007, mainly driven by biomass growth, which has become the second largest energy source. Wind power has also shown impressive growth rates (0.2% to 3% between 2011 and 2015 - 1,400% growth), particularly in the last two years, but its share is still low. In contrast, oil and derivatives have been reducing its share, decreasing from 53% to 42% between 2011 and 2015. In addition, 2015 was the third consecutive year without importing electricity from Argentina [12].

The significant growth of energy generation from renewable sources since 2007 is shown in Figure 2—4. While the share in the total energy supply increased in small extent due to the demand growth, the energy produced from renewable sources has nearly tripled in ten years (2006 – 2015), showing a steady increase.

**Figure 2—4 Evolution of energy supply per type 1990 - 2015**



*Source: DNE* [12].

Uruguay has drastically changed its energy system in the last decade, moving from a strong dependency on fossil fuels to a diverse, distributed and indigenous energy matrix. The model consists in clear government's mandates and guidelines, tax incentives and strong private sector involvement [20].

In addition, the Uruguayan government has set a strong regulatory framework and it has included investments in clean energy technology within the "Investment promotion and protection" Act, which provides a set of incentives and tax benefits to projects of great public interest.

### *2.3.2 Electricity sector*

#### 2.3.2.1 Structure of the electricity sector

The electricity sector in Uruguay is governed by Act 16,832 and further derivate regulations. They establish that distribution and transmission activities are public services, while generation and commercialisation can be done by public or private actors. Likewise, electricity must be dispatched through the National Dispatch Office, and in accordance with the regulations of the electricity wholesale market.

The relevant public actors in the electricity sector in Uruguay are:

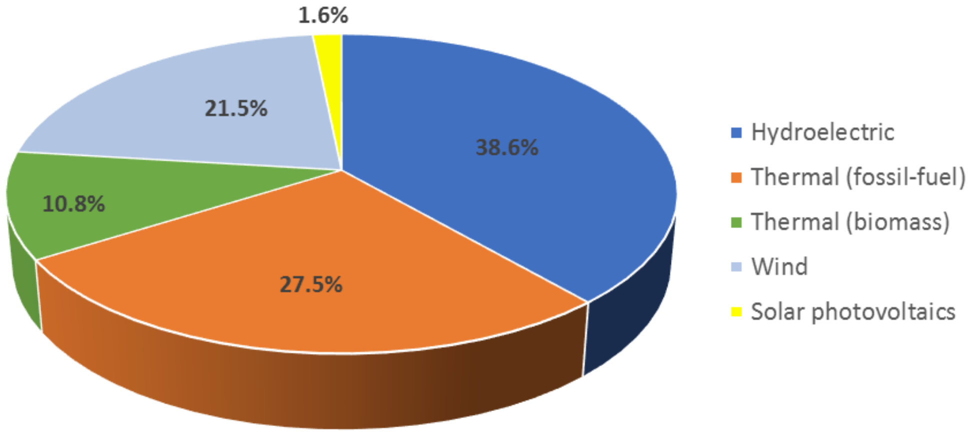
- DNE, MIEM: government agency responsible for formulating and implementing the energy policy, introducing regulations and coordinating the public and private actors.
- *Unidad Reguladora de Servicios de Agua y Energía*: government agency responsible for regulating and inspecting safety, quality and consumer protection issues.
- UTE: government electricity company, which develops enterprise activities in terms of electricity generation, transformation, distribution, transmission and commercialisation.
- *Administración del Mercado Eléctrico*: public entity responsible for managing the electricity wholesale market and the National Dispatch Office.

Currently, the common scenario is UTE generating or buying electricity from private generators, and then transmitting, distributing and commercialising that electricity to final consumers. In recent years, it has signed power purchase agreements with private generators to buy electricity from renewable sources through auctions (large-scale) and feed-in tariff scheme (small-scale). Auctions have helped non-conventional renewable sources to achieve competitive prices [20].

#### 2.3.2.2 Total installed capacity

In terms of electricity generation, Uruguay has four hydroelectric power plants (one of them share with Argentina), thermal power stations (fossil-fuel and biomass), wind and solar farms, microgeneration and self-generation. Likewise, it has interconnection networks with Argentina (2,000 MW) and Brazil (570 MW). Between 2005 and 2015, the total installed capacity increased 95%, mainly due to the incorporation of renewable sources [12]. The composition of the total power installed capacity by 2015 is shown in Figure 2—5 and Table 2—3.

**Figure 2—5 Installed capacity per source – Uruguay 2015**



*Source: DNE* [12].

The installed capacity has been significantly diversified in the last decade regarding energy sources. Before 2005, the system was almost entirely composed by fossil-fuel thermal power plants and large-scale hydroelectric power plants. However, since 2006, biomass, wind power and, incipiently, solar power have been integrated to the electrical system.

**Table 2—3 Composition of the total installed capacity by 2015**

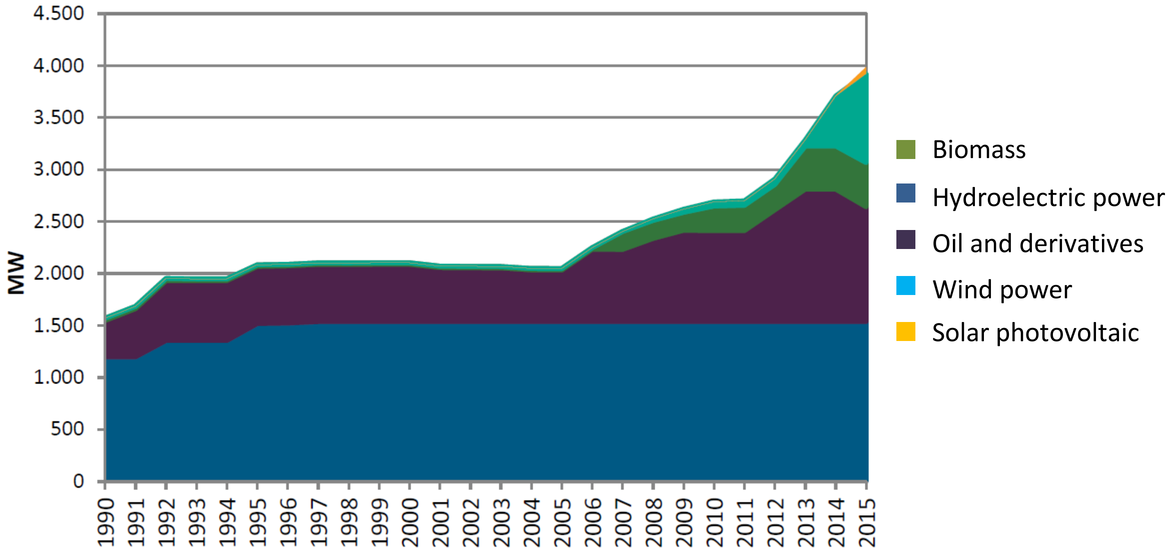
| Source | Installed Capacity (MW) | Share |
|---|---|---|
| Hydroelectric plants | 1,538 | 38.6% |
| Thermal power stations | 1,530 | 38.4% |
| *Fossil-fuels* | *1,098* | *27.5%* |
| *Biomass* | *432* | *10.8%* |
| Wind power plants | 857 | 21.5% |
| Solar photovoltaic plants | 64 | 1.6% |
| *Installed capacity per source type* | | |
| Renewable sources | 2,891 | 72.5% |
| Non-renewable sources | 1,098 | 27.5% |
| ***Total*** | ***3,989*** | ***100%*** |

*Source: DNE* [12].

It is worth noting that Uruguay reached its maximum large hydroelectric power exploitability in 1995, so the sustainable expansion of the electrical system must rely on other renewable sources. Thus, non-conventional renewable capacity has been significantly growing in recent years. Biomass went from 22 MW in 2006 to 432 MW in 2015, wind power went from 60 MW in 2013 to 857 MW in 2015 and solar photovoltaics increased from 1 MW to 64 MW in the same period [12]. The evolution of the installed capacity in the last 25 years is shown in Figure 2—6.

The electricity delivered by hydroelectric power plants is highly dependent on the hydrological resource, which inevitably varies every year. Before the recent process of matrix diversification, hydrological resource availability and fossil fuel consumption were closely linked, which made Uruguay highly vulnerable to weather conditions and changes in international oil prices. What is more, this scenario of vulnerability was foreseen to progress into more uncertain situations considering climate change effects and increasingly common geo-politics issues.

**Figure 2—6 Installed capacity per source 1990 - 2015**

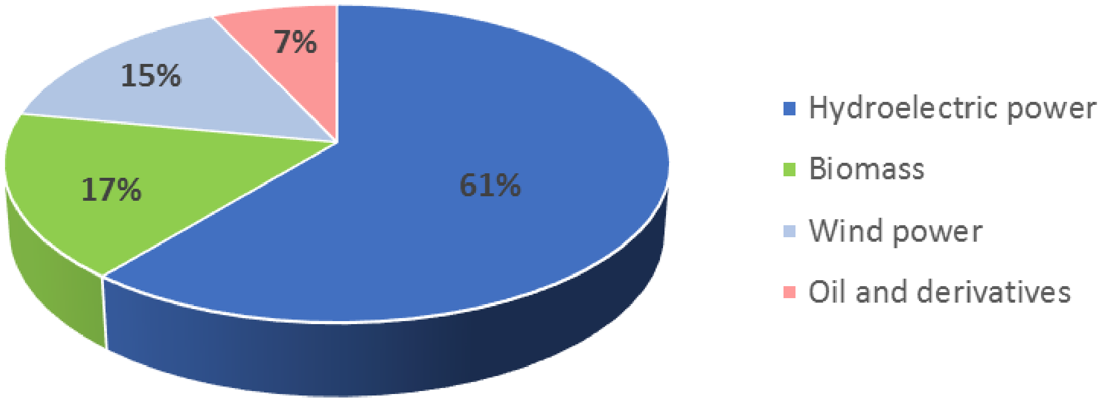


*Source: DNE* [12].

2.3.2.3 Electricity supply

In 2015, renewables accounted for 93% of total electricity generation, with a contribution of 32% from non-conventional sources [12]. This figure, largely overcome the 15% goal of the *Energy Policy 2005–2030*. Despite being a year of poor hydrological resource, the growth of biomass (26%) and wind power (300%) between 2014 and 2015 allow the system to reach a high level of renewable share. Electricity was generated mainly by hydroelectric power plants (61%), followed by biomass (17%), wind power (15%), fossil fuels (7%) and solar photovoltaics (< 1%) [12]. Electricity generation per source is shown in Figure 2—7.

**Figure 2—7 Electricity generation per source 2015**



Note: Solar photovoltaic power is not represented due to its small share in the mix.

*Source: DNE* [12].

It is also interesting to analyse how the electricity supply has evolved in recent years. Its evolution between 2011 and 2015 is presented in Table 2—4. As mentioned before, hydroelectric power is highly dependent on hydrological resources, which change every year. In consequence, its share in the electricity supply can widely vary in consecutive years.

The most impressive outcome is the reduction of oil and derivatives (26% to 7% - 2011/2015) driven by the large increase generation both from biomass (3% to 17% - 2011/2015) and wind power (1% to 15% - 2011/2015) [12]. Consequently, the renewable electricity share increased from 69% to 93% between 2011 and 2015. During the same period, the share of solar photovoltaic remained under 1%, which shows that this technology has been relegated in relation to the other renewable sources.

**Table 2—4 Evolution of the electricity supply 2011 - 2015**

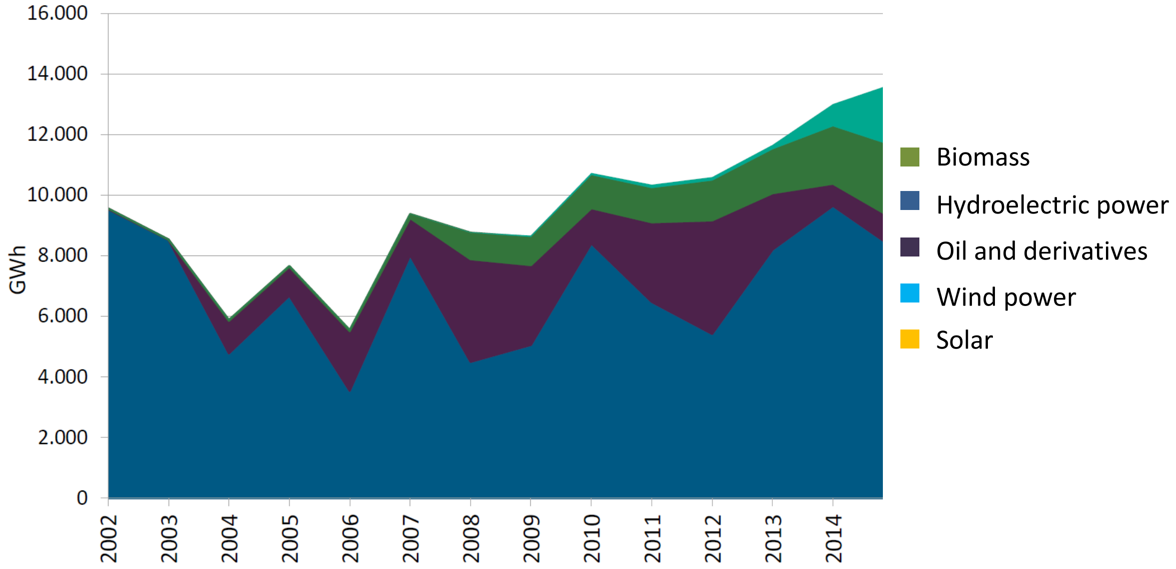
| **Source** | **2011[a]** | **2012[b]** | **2013[c]** | **2014[d]** | **2015[e]** |
|---|---|---|---|---|---|
| Hydroelectric power | 65% | 51% | 70% | 74% | 61% |
| Biomass | 3% | 5% | 12% | 14% | 17% |
| Oil and derivatives | 26% | 36% | 16% | 6% | 7% |
| Wind power | 1% | 1% | 1% | 6% | 15% |
| Solar power | < 1% | <1% | < 1% | < 1% | < 1% |
| Imported electricity | 5% | 7% | 0% | 0% | 0% |
| *Total from renewables* | *69%* | *57%* | *83%* | *94%* | *93%* |

*Source:* [a]*ADME* [21]; [b]*ADME* [22]; [c]*DNE* [15]; [d]*DNE* [19]; [e]*DNE* [12].

The evolution of the electricity generation per source in recent years is shown in Figure 2—8, where the high variation of hydroelectric power can be observed. Before 2007, fossil fuels were the only complementary source, but renewables have been increasingly replacing them, with outstanding results since 2013.

As can be seen, the development of the electricity sector in Uruguay has largely exceeded expectations, achieving high levels of source diversification in recent years. However, considerable work remains to be done if Uruguay is to be effectively independent from external factors, such as changes in international oil prices and weather conditions. In this context, with biomass and wind been strongly developed, there is a chance for solar photovoltaic to become a relevant part of the electricity mix, continuing in the road of diversifying as much as possible the sources.

**Figure 2—8 Evolution of electricity generation per source 2002 - 2015**



*Source: DNE* [12].

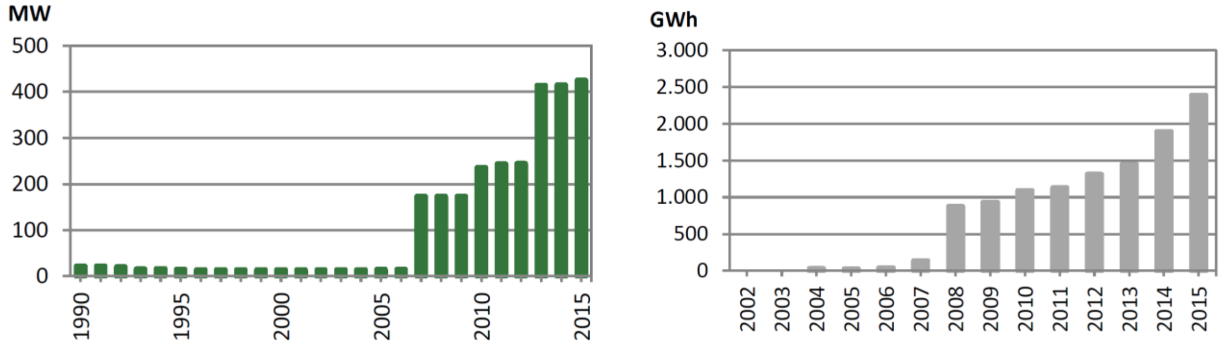
### *2.3.3 2016 and perspectives*

Renewables are growing at vertiginous rates in Uruguay, particularly in the last five years. 2016 was not the exception, and even though the BEN 2016 will not be published until October 2017, there are some data available that show relevant changes in the energy and electricity mix. Likewise, information about new projects in planning and construction stage allows estimating future scenarios.

Whilst all non-conventional renewables have increased their installed capacity in recent years, the case of biomass has been peculiar. The significant growth in biomass is mainly related to the operation of two cellulose pulp production plants, namely UPM and Montes del Plata [12]. Both plants generate electricity from biomass and sell their surpluses to UTE, with a total installed capacity of 341 MW (79% of total biomass capacity). UPM with 161 MW entered operation in 2007, while Montes del Plata with 180 MW entered operation in 2013 and started operating at full capacity in 2015 [23].

Biomass installed capacity and electricity generation in recent years are shown in Figure 2—9, where is clearly observed the effect of both plants in the biomass growth. Due to this fact, it is not expected new jumps in biomass installed capacity in the short-term. In contrast, wind and solar power development have been different and they are discussed later in this work.

**Figure 2—9 Installed capacity and electricity generation from biomass**



**Biomass installed capacity 1990 - 2015** **Electricity generation from biomass 2002 - 2015**

*Source: DNE* [12].

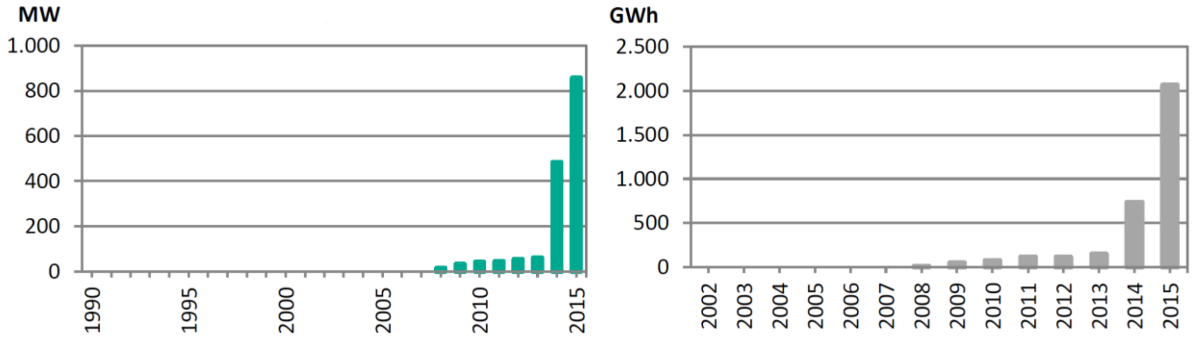
According to data from UTE, renewables accounted for 96% of total electricity generation in 2016. Wind energy increased 45.2% between 2015 and 2016, while photovoltaics energy increased 230.5% in the same period. Hydroelectric power and biomass did not change significantly, with rates of -5.8% and 4.0% respectively. In contrast, thermal generation from fossil fuels decreased 53.6%. Furthermore, the increment in wind and solar energy (1,028,796 MWh) largely overcame the decrement in fossil fuels generation (-496,749 MWh) [24]. From these data, it could be expected a larger share of renewables in the primary energy supply mix, and particularly in the electricity mix for 2016.

### 2.3.3.1 Wind and solar development

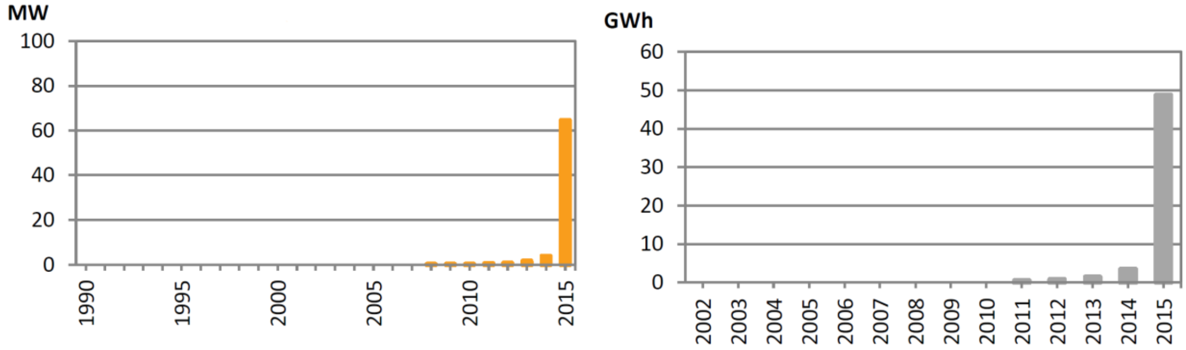
The *Energy Policy 2005–2030* focuses on the development of renewable and indigenous sources for energy generation and, undoubtedly, wind power has played an essential role so far. Solar photovoltaic energy has just started to be developed following a steady reduction in technology prices, but it still has a marginal share in the electricity mix, exceeding 1% of total electricity produced for the first time in 2016 (1.27%) [24]. Wind and solar installed capacity and electricity generation in recent years are shown in Figure 2—10.

Despite having a valuable solar resource, the solar photovoltaic technology was not exploited at large scale in Uruguay until 2013, when “Asahi”, a 500 kW pilot-plant, entered operation in the north of the country [12], as a result of a collaboration between the Uruguayan and the Japanese governments [15]. Following Asahi, two large-scale solar photovoltaic power plants entered operation in 2015 (La Jacinta and Raditan) with a total capacity of 58 MW and one more started to generate electricity in 2016 (Alto Cielo) with a capacity of 20 MW [25].

**Figure 2—10 Installed capacity and electricity generation from wind and solar**



**Wind power installed capacity 1990 - 2015** **Electricity generation from wind 2002 - 2015**



**Solar power installed capacity 1990 - 2015** **Electricity generation from solar 2002 - 2015**

*Source: DNE* [12].

Even though solar photovoltaic development is still incipient in Uruguay, solar energy has been boosting since 2009, through the promotion of solar thermal technologies. A mandate to install solar thermal equipment in new constructions and refurbishment came into force in 2009, particularly for eligible buildings where heating water accounts for over 20% of the total energy consumption of the building (eg public offices, health facilities, sport clubs, hotels). This regulation also established that the government may request new industries to carry out technical studies to assess the potential use of solar thermal equipment for heating water [9].

In the context of the solar thermal promotion, financing opportunities, subsidies and tax benefits were introduced by the DNE, UTE, *Banco de Seguros del Estado* (public social insurance bank) and *Banco Hipotecario del Uruguay* (public mortgage bank). This promotion represents a clear example of the government's intention to develop solar energy, as stated in the *Energy Policy 2005-2030.*

The late development of the solar photovoltaic technology has been mostly consequence of its high investment costs. It was not included in the first renewable energy auctions because it was considered to be significantly more expensive than other sources. However, as a result of the substantial decline in the technology prices, it was finally incorporated in 2013 (Decree 133/013), when the government launched a call for large-scale solar photovoltaic projects [9].

Asahi, La Jacinta, Raditan and Alto Cielo are the four large-scale photovoltaic power plants that have entered operation in Uruguay since 2013. In addition, 7.4 MW of microgeneration and auto generation have also been installed up to 2016, summing up 85.9 MW of total installed capacity [25]. According to information from DNE, other fifteen large-scale solar photovoltaic projects are in planning or construction phase, amounting to 158.1 MW additional capacity [23].

Solar photovoltaic technology is growing at increasing rates, but its share in the electricity mix is still incipient taking account of the resource potential and the benefits it can provide in terms of source diversification. In the years to come, the complementarity between wind and solar resources is expected to play a key role in developing the solar photovoltaic technology in Uruguay, contributing to reduce the total cost of the electricity system [26].

### *2.4 Complementarity of resources*

Wind and solar resources have been assessed worldwide in terms of their complementarity, showing that their combination improved the predictability and reliability of energy systems. Even though the complementarity is highly location-dependant, there is extensive evidence showing a common inverse dependency between both resources, with more wind typically available during winter and night and solar being prevalent during summer and day time [27]–[30].

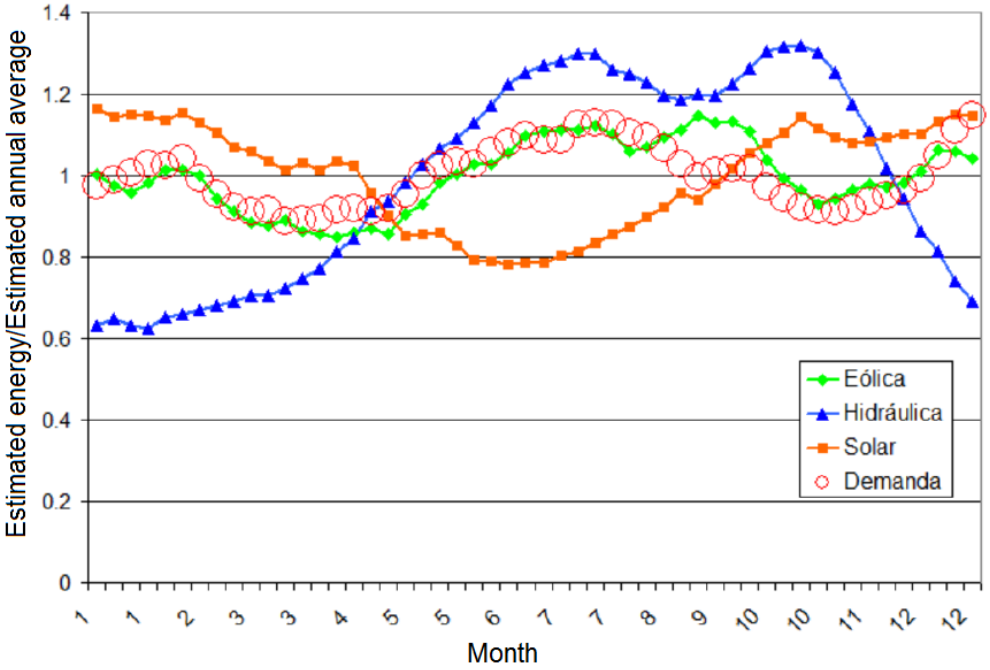
Following this observation, the Uruguayan Government is specially interested in evaluating the complementarity between solar and wind resources for power generation at national level. In recent years, the DNE has commissioned technical studies on this subject to the School of Engineering of Universidad de la República - Uruguay (hereafter FING-UdelaR) and other engineering institutions, which have been supported by *Agencia Nacional de Investigación e Innovación* (ANII) of Uruguay and *Agencia Española de Cooperación Internacional para el Desarrollo* (AECID) of the Spanish Government.

These studies have been conducted to evaluate possible scenarios for the expansion of the electricity system in Uruguay, using integral models to account for the potential of the complementarity between solar and wind resources in meeting the electricity demand efficiently. They also aim at assessing the potential of the mix solar-wind as an alternative to the installation of thermal back-up or energy storage for the strengthening of the electrical system.

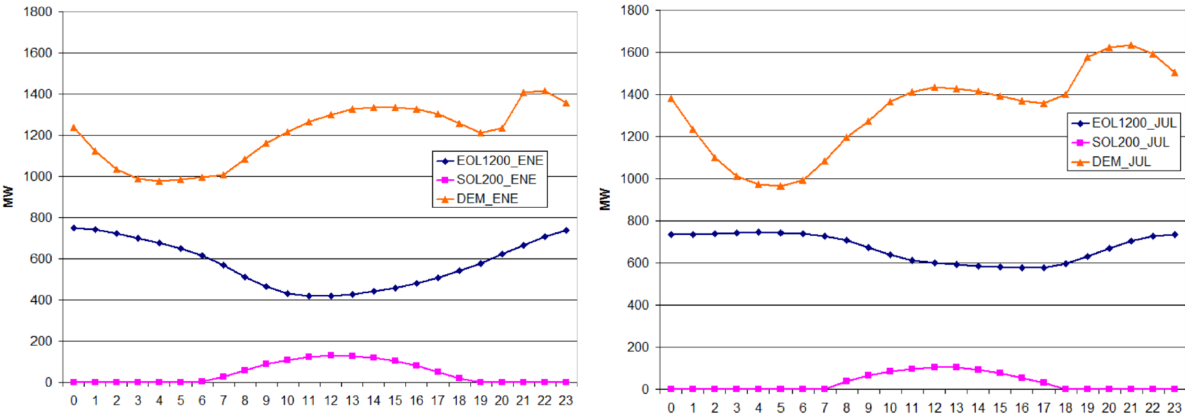
Chaer *et al.* (2014) and Gurin *et al.* (2016) have demonstrated that the complementarity between wind and solar resources in Uruguay has positive effects on the energy availability in comparison with both technologies separately. Both reports showed that there exist direct correlations between increasing solar energy generation and decreasing wind energy production within daily and seasonal cycles (ie sunny and cloudy, day and night, summer and winter).

These correlations can be clearly observed in the charts presented in the Chaer *et al.* report (Figure 2—11), of daily and annual expected generation for wind, solar and hydroelectric power, as well as the expected demand. During winter (May to September) there is an important decrease in solar power generation and a slightly increase in wind power generation. In contrast, during summer (November to March), solar power increases significantly, and wind power presents lower values. Likewise, for the daily cycle, both during summer (January) and winter (July) wind power generation decreases when solar power generation increases (7 am to 6 pm).

**Figure 2—11 Correlation between solar and wind power generation**



Annual energy expected generation for wind (green), solar (orange) and hydroelectric power (blue), as well as expected demand (red circles) per month (abscissa axis).



Average daily expected energy generation for wind (blue) and solar (violet), as well as expected demand (orange) per hour (abscissa axis) for January (left figure) and July (right figure).

*Source: Chaer et al., 2014* [31].

The complementarity effect described by Chaer *et al.* and *Gurin et al.* is promising when considering the expansion of the electrical system. It means that this expansion could rely on solar energy, provided that the development of the photovoltaic technology is economically viable. It also means that Uruguay could avoid or delay the installation of thermal back-up and energy storage systems. As a result, solar photovoltaic development has the potential to play a key role in complementing the current renewable energy mix and strengthen the sovereignty of the Uruguayan energy system in the most sustainable way [11]. However, the cost of the solar photovoltaic technology in Uruguay remain a major issue, preventing it from being fully developed. In this context, options must be evaluated to bring down the costs of solar photovoltaic projects.

### *2.5 Hybrid solar-wind farms*

Solar and wind power plants co-located and connected at the same point of the grid is a relatively novel concept for renewable energy production. This type of power plant is still in an early developmental stage, with few studies and limited data available to this day. Countries that have made progress on this subject include Australia and India, which have started to develop projects and regulations. In contrast, no information is available on wind-solar power plants in South America up to day.

The Ministry of New and Renewable Energy of India published a consultation paper on hybrid farms in 2016, where it stated the government interest in promoting this concept of power production through financial incentives and fiscal benefits. The *Draft National Wind-Solar Hybrid Policy* established guidelines for hybridising existing power plants and planning new ones.

This paper highlighted the potential of such a plant layout in optimising infrastructure and land use, as well as buffering the intermittency of the energy sources. Likewise, it also evaluated the effect of different technologies and plant structures in planning the most effective strategy for developing hybrid farms [32].

Australia has also begun to develop co-located wind and solar power plants lately. In 2016, the first hybrid farm project was announced by the Australian Renewable Energy Agency (hereafter ARENA). This project has been developed to hybridise an existing 165.5 MW wind farm near Canberra, by adjacently installing a 10 MW solar photovoltaic plant. According to the developers, up to 20% of the solar photovoltaic project cost could be saved by hybridising the existing wind power plant [33], [34].

In this context, a study on the potential for developing other hybrid wind-solar farms in Australia was commissioned by ARENA in 2016. According to this study, there are key areas were significant savings can be made by installing a solar farm adjacent to an existing wind farm, namely planning, infrastructure development, operation and maintenance. The study has also highlighted the benefits of such a power plant layout in terms of stability of supply and capacity factors at the points of connection to the grid.

Overall, it was estimated that capital cost savings could be between 3% to 13%, while operational cost savings could be between 3% to 16% [35].

In addition, the Australian Government has expressed its interest in developing hybrid farms based on the good complementarity between wind and solar resources for energy production, emphasising their advantages in infrastructure and land use optimisation, as well as their environmental benefits [34].

As can be seen, installing a solar photovoltaic power plant adjacent to an existing wind farm have the potential to significantly reduce project costs. This concept may represent an innovative strategy to promote the solar photovoltaic technology in Uruguay, where a large number of wind power plants have been installed in recent years and the government is especially interested in developing solar energy as a complementarity source to the existing renewable mix [11].

## *2.6 Environmental aspects related to solar energy projects*

### *2.6.1 Overview*

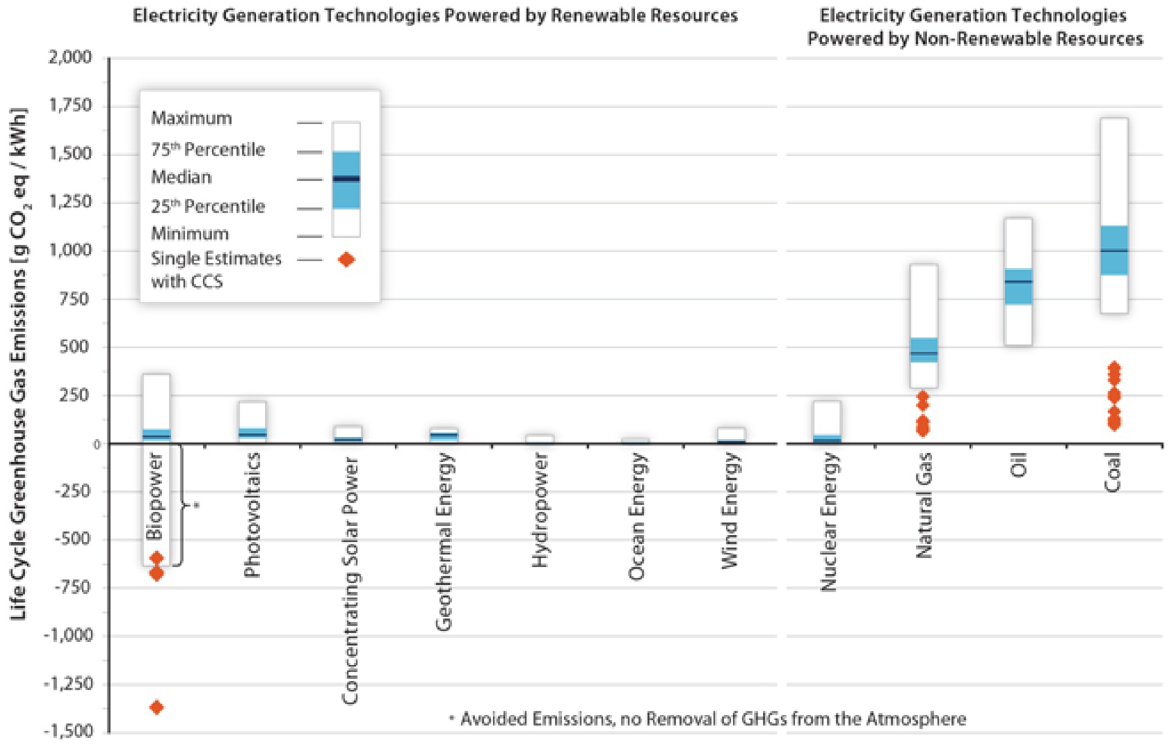
The expansion of renewable energy technologies is linked to well-known environmental benefits, mostly related to their potential to reduce carbon dioxide and other greenhouse gases (hereafter GHG) emissions [11]. According to the Intergovernmental Panel on Climate Change (hereafter IPCC), there is robust evidence and high agreement on the energy supply sector being one of the greatest contributors to GHG emissions worldwide [36].

In this context, the IPCC acknowledges that the stabilisation of GHG concentration in the atmosphere at acceptable levels will require radical changes in the energy sector, including the substitution of fossil-fuel conversion technologies by less carbon-intensive alternatives, such as renewable energy [36]. Figure 2—12 shows an estimation of lifecycle GHG emissions for both renewable and non-renewable technologies, published by the U.S. National Renewable Energy Laboratory.

Furthermore, renewable energy technologies not only play a key role in reducing GHG emissions, but they also contribute to avoid depletion of natural resources, reduce pressure over sensitive ecosystems and minimise degradation of land. At a local scale, they also help to preserve water resources, keep air quality and maintain noise to acceptable levels, among other socioeconomic benefits (eg employment creation and development of local capacities) [38].

However, despite the well-known environmental benefits, renewable energy technologies also produce negative impacts throughout their complete lifecycle (eg manufacturing, transportation, construction, installation, maintenance, decommission and waste management). Each technology has different impacts associated, and they all must be considered if the expansion of the energy sector is to be truly sustainable.

**Figure 2—12 Lifecycle GHG emissions for renewable and non-renewable technologies**



*Source: U.S. National Renewable Energy Laboratory* [37].

Particularly, the solar photovoltaic technology has the additional advantages of being inherently safe during operation, as well as producing no noise and causing no air pollution while generating electricity [39]. Nevertheless, the following potential negative environmental impacts have been reported for this technology [38][39]:

- Land use, land degradation and habitat loss due to the spatial distribution of the power plant. This impact could be minimised by locating the plants in low-quality sites, or existing transmission corridors.
- Landscape alteration/visual impact, particularly for areas of outstanding natural beauty.
- Use of resources during the manufacturing process (eg water, silicon and metals).
- Contamination of water bodies and soil during maintenance operations and/or waste management.
- Air pollution, contamination of water and soil, increase of heavy traffic, disturbance to biotic environment and noise during the construction phase of the power plant.
- Air pollution and water contamination by chemicals used in the photovoltaic cells production in the manufacturing facility, installation site and disposal or recycling points.

All the above-mentioned impacts must be considered when planning, constructing and operating a solar photovoltaic power plant in Uruguay. The latter is not only part of good environmental practices, but a regulatory requirement of the *Dirección Nacional de Medio Ambiente (*hereafter DINAMA), the governmental agency responsible for the preservation of the environment.

### *2.6.2 Environmental regulatory framework for solar projects in Uruguay*

Uruguay has developed an integral environmental regulatory framework for any venture that may have detrimental effects over the environment. In this context, DINAMA is responsible for formulating the policies and regulations, defining the standards, giving the required permissions and monitoring the activities of every project within the country [11].

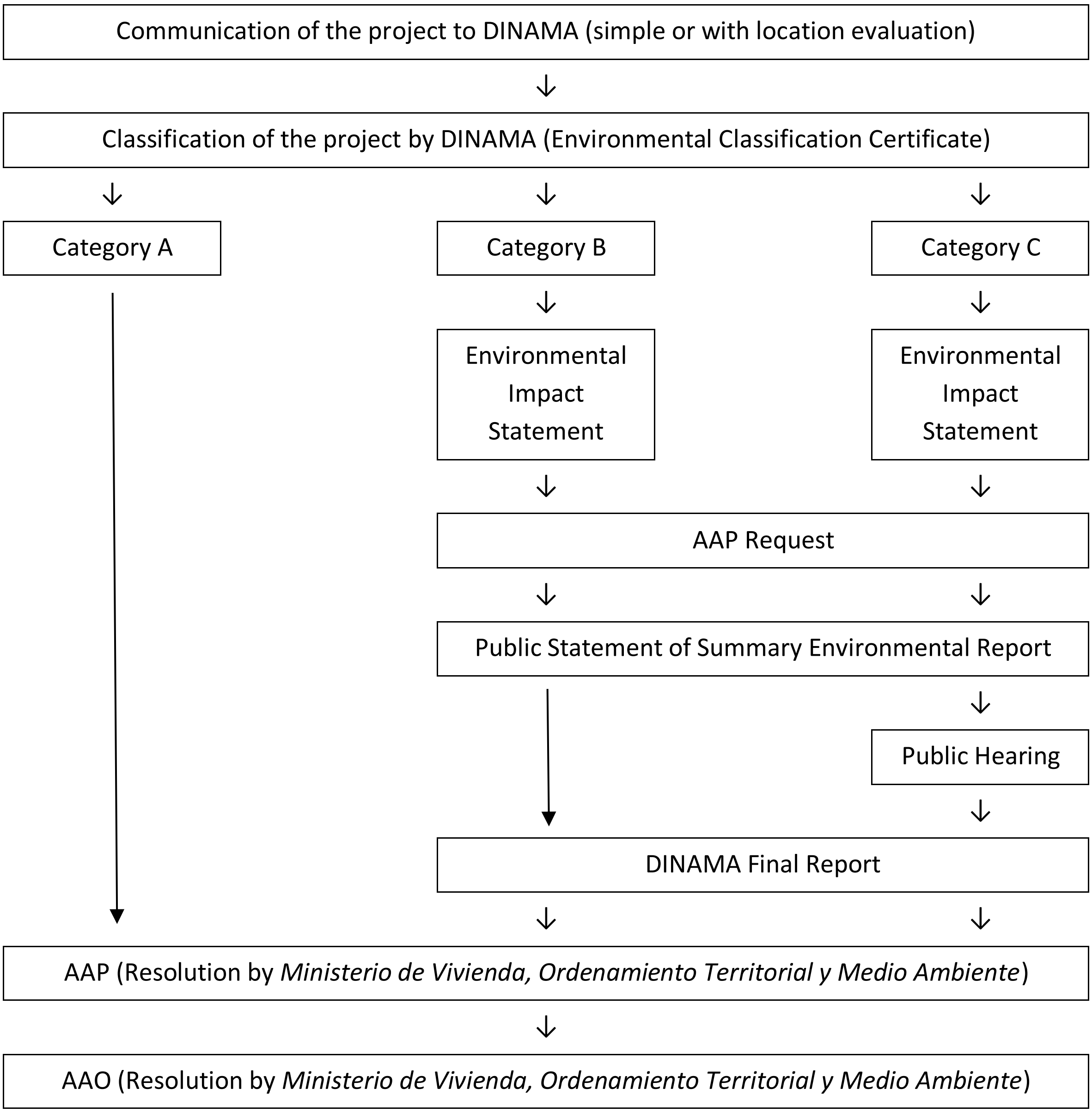
The current regulation requires any venture that may produce negative impacts to get mandatory authorisations before being constructed and operated. The Decree 349/005 established the "Environmental Impact Assessment and Environmental Permits Regulation", which defined the two main permissions needed for these projects to be developed, namely the *Previous Environmental Permit* (hereafter AAP) and the *Operation Environmental Permit* (hereafter AAO).

Within the framework of these permissions, a series of administrative requirements may be requested to the developer according to the nature and magnitude of the project. These may include an approval of the location and a comprehensive Environmental Impact Assessment if DINAMA considered them necessary.

Decree 349/005 establishes that construction of power plants of 10 MW or more (whatever its primary source is), as well as renovation of existing ones (increasing capacity or change in the primary source) will require AAP and AAO to be developed. Thus, any solar photovoltaic power plant of 10 MW or more must comply with these requirements and therefore, apply to DINAMA for getting the permissions.

The process for a project to get the permissions by DINAMA is summarised in Figure 2—13.

**Figure 2—13 Regulatory process for a project to get the environmental permissions**



*Source: DINAMA [40].*

# 3 Methodology

## *3.1 Economic analysis of hybrid farms*

### *3.1.1 Investment costs of solar photovoltaic projects*

The investment costs of solar photovoltaic projects in Uruguay were estimated from a report commissioned by the DNE to *KPMG* and *SEG Ingeniería* in 2015 [41], where the national component share of the investment and the socioeconomic impacts of renewable energy projects were analysed. Within the report, investment costs for solar photovoltaic projects were established and divided into 18 categories for three sizes of power plants (10 MW, 50 MW and 100 MW). Likewise, the costs were determined for two possible scenarios considering the share of the national component of the investment (maximum and minimum).

To estimate the investment costs of a solar photovoltaic power plant in the context of this dissertation project, the average cost between the scenarios of maximum and minimum national component share of the investment was calculated. On that basis, the costs of the 18 categories for each of the three different sizes of power plants were calculated, considering their share in the total investment. These costs were expressed standardised to the unit of power in alternate current (hereafter AC) as investment costs per MW installed in AC (USD/MW).

As explained before, the price of the solar photovoltaic technology has been sharply decreasing in recent years and, consequently, data from 2015 were likely to be out-of-date, leading to misguided assumptions. Therefore, the costs established in the *KPMG and SEG Ingeniería* report were revised and updated based on new data requested to DNE.

It is worth noting that the DNE has updated data only for 50 MW power plants, but the capacities to be analysed in this dissertation project are in the range of 5 MW to 25 MW. Thus, correction factors were calculated for each of the 18 categories considering the evolution of the prices between 2015 and 2017 for a 50 MW power plant. In all cases, the calculations were made at a constant dollar rate (base May 2017) to eliminate effects from changes in the currency rate. The correction factors (Θ) were calculated according to Equation (1):

$$\theta_i = \frac{Cost_{i\,2017}\,(\frac{USD}{MW})}{Cost_{i\,2015}\,(\frac{USD}{MW})} \qquad (1)$$

Where $\theta_i$ represents the correction factor of a given category, $Cost_{i\,2017}$ represents the cost of that category in 2017 (updated according to DNE data), and $Cost_{i\,2015}$ represents the cost of the same category in the 2015 *KPMG* and *SEG Ingeniería* report (converted at a May 2017 based dollar rate).

The correction factors for each category were then used to update the investment costs for a 10 MW solar photovoltaic power plant, which were also converted to a May 2017 based dollar rate.

After estimating the costs, consultations were made to electrical engineers in charge of renewable energy projects in Uruguay to establish which of the 18 categories would apply (and to which extend) to a solar photovoltaic power plant installed adjacent to an existing wind farm. As a result, only the categories that were considered to apply for a power plant of such a layout were taking into account to calculate the total investment costs of the hybrid configuration.

### 3.1.2 Operation and maintenance costs of solar photovoltaic developments

Operation and maintenance (hereafter O&M) costs were also take from the *KPMG* and *SEG Ingeniería* report. In this case, costs were divided into six categories, namely land rent, parts and consumables, salaries, reparations, insurance and replacement of equipment.

The O&M costs established in the *KPMG* and *SEG Ingeniería* report were the result of market research and interviews with national and international developers. Despite being from 2015, they were deemed to be valid for this dissertation project as there are no records of major changes in O&M costs in recent years in Uruguay.

### 3.1.3 Revenues from a hybrid farm

The annual revenue of any solar photovoltaic power plant configuration in Uruguay is the result of the energy dispatched to the grid and the price paid by UTE for that energy, as established in the Power Purchase Agreement (hereafter PPA) contract.

According to information from the DNE, UTE has signed PPAs with wind and solar power producers for 25-years projects at fixed energy prices (single hourly rate). As a result, the present analysis can be decoupled from the effect of time, since the energy price is the same throughout the 8,760 hours of the year. The latter is relevant for the economic analysis, since it can be conducted considering energy losses on an annual basis. Otherwise, the system will require hourly basis analyses, which will require more data and more powerful modelling tools.

Hence, given the precedent conditions of the PPAs between UTE and private producers, the revenues of a solar power plant installed adjacent to an existing wind farm can be calculated according to Equation (2):

$$Revenue\left(\frac{USD}{year}\right) = Energy_{produced}\left(\frac{MWh}{year}\right) \times (1 - Energy\ lost\ rate) \times Price^{1}\left(\frac{USD}{MWh}\right) \quad (2)$$

---

[1] Price is adjusted annually by a parametrical curve established in the PPA contract. A simplify version of the last licencing round's parametrical curve was used, where the energy price is adjusted by the ratio U.S. Producer Price Index (year n) to U.S. Producer Price Index (year 0) for Finished Goods (Code: WPUFD49207).

The *Energy Lost Rate* represents the percentage of the energy produced by the system that could not be dispatched due to restriction in the transmission grid capacity, and it was determined for different power plant configurations by *Gurin et. al* [26]. This rate is discussed in the section *Technical alternatives for co-location of solar and wind farms in Uruguay* in the chapter *Economic analysis*.

The price of the energy in the last licencing round for large-scale solar photovoltaic projects of UTE was 86.6 USD/MWh in 2013 (Decree 133/013). Nevertheless, according to information from the DNE, it is expected that the energy price for the next licencing round will be in the range of 65 USD/MWh, following the reduction in the international prices of the technology.

For the economic analysis, the energy price was taken as a sensitivity parameter and therefore, three different scenarios were analysed. The energy prices considered were 65 USD/MWh, 70 USD/MWh and 75 USD/MWh.

### *3.1.4 Energy produced*

The energy produced for a solar photovoltaic power plant is directly proportional to its total installed capacity. The latter was taken as a sensitivity parameter and therefore, three different figures were considered, namely 5 MW, 15 MW and 25 MW.

It is worth noting that the capacities of the power plants are expressed in AC, which means that they represent the output power at the transformer terminals. The other way to express the capacity of a solar photovoltaic power plant is as the sum of the power rates of the photovoltaic modules (direct current). However, the output of any solar photovoltaic power plant must account for the energy losses in the transformation DC-AC, which are commonly estimated in 20% [26], [41]. In the present study, all power plant capacities are expressed in AC.

The energy produced per year was calculated using Equation (3):

$$Energy(kWh) = \sum_i Irradiation\left(\frac{kWh}{m^2\ day}\right) \times Area\ (m^2) \times n\ \left(\frac{days}{month}\right) \times \eta \quad (3)$$

Where $i$ represents the months from January to December, $Irradiation$ is the daily average global irradiation on a 25° titled surface, $Area$ represents the effective area of solar cells for a given installed capacity, $n$ is the number of days for a given month and $\eta$ is the module efficiency.

The irradiation data was provided by the *Laboratorio de Energía Solar* (hereafter LES) of FING-UdelaR, after a formal request of information for the site of *Pampa* wind farm. Daily averages of global irradiation were provided on a monthly basis for 7 years (2010-2016), both for horizontal and titled surfaces (25° as the optimum angle for the latitude of *Pampa* wind farm). The averages of the 7-years data for titled surfaces were used for the calculations of the energy production.

The effective area of solar cells and module efficiency were taken from the data sheet of a JAP6 72-315/3BB multicrystalline silicon module from JA Solar, one of the most common solar modules used in Uruguay.

### *3.1.5 Economic evaluation of hybrid farm projects*

The economic assessment of the different system configurations and the comparison between them was conducted following traditional methodologies of project evaluation, considering the concepts of discounted cash flow and time value of money (money values throughout the entire lifetime of the project were referred to present by their Net Present Value (NPV)).

In this context, the methodologies used included Net Lifetime Cost (LC), which could also be expressed as Cost/Benefit Ratio (CBR), Payback Period (PP), Internal Rate of Return (IRR) and Levelized Cost of Energy (LCOE). All of them are commonly used when conducting project economic appraisal or comparisons among alternative designs [42], and are calculated as follows:

- Net Lifetime Cost (LC) and Cost/Benefit Ratio (CBR)

$$LC(USD) = NPV\ Costs(USD) - NPV\ Benefits(USD) \quad (4)$$

$$CBR = \frac{NPV\ Costs(USD)}{NPV\ Benefits(USD)} \quad (5)$$

Where NPV Costs and NPV benefits are calculated according to Equation *(6)* and *(7)* as follows:

$$NPV\ Costs(USD) = \sum_i \frac{O\&M_i + Financial\ cost_i + Taxes_i + Amortization_i + Capital_i}{(1 + interest\ rate)^i} \quad (6)$$

$$NPV\ Benefits(USD) = \sum_i \frac{Revenues_i(USD) + Loans_i\ (USD)}{(1 + interest\ rate)^i} \quad (7)$$

According to Equations *(4)* and *(5)*, feasible projects would have a negative LC (benefits overcome costs) and a CBR < 1. In contrast, non-feasible projects would have a positive LC and a CBR > 1. The more negative the LC value (lower CBR), the project will produce the higher return of investment, whereas the more positive the LC value (higher CBR), the project will produce greater economic losses. These methodologies are useful to evaluate whether a project would be profitable or not, but are not appropriate to make comparisons among projects of different size and type [42].

- Payback Period (PP)

The Payback Period represents the time when the LC of a project equals zero, and consequently, the project starts to produce a profit. This parameter is calculated based on the cumulative cash flow of the project (hereafter ccf) according to Equation *(8)*.

$$PP\ (years) = Last\ year\ with\ negative\ ccf + \frac{|Last\ negative\ ccf|}{Cash\ flow\ (1^{st}\ year\ of\ positive\ ccf)} \quad (8)$$

- Internal Rate of Return (IRR)

The Internal Rate of Return represents the equivalent interest rate at which the LC of a project equal zero. This parameter could be used to compare with the actual interest rate to determine whether a project would produce higher returns than an investment at that given interest rate or not. The IRR is also useful to compare two or more different projects, the higher the IRR, the more profitable the project [42]. The IRR could be calculated by iteration.

- Levelized Cost of Energy (LCOE)

Finally, the Levelized Cost of Energy is a method to evaluate the competitiveness of diverse energy technologies or alternative designs. It represents the cost per unit of energy produced taking account of the entire lifetime project costs (investment, O&M, financing, amortization of loans and taxes) [43]. The LCOE should be assessed together with the energy price, as their relationship would determine whether a project would be profitable or not.

LCOE is calculated according to Equation *(9)* as follows:

$$LCOE(USD) = \frac{NPV\ Cost\ (USD) + Loan(USD)}{\sum_i \frac{Energy\ produced_i \left(\frac{MWh}{year}\right) \times (1 - Energy\ lost\ rate)}{(1 + interest\ rate)^i}} \quad (9)$$

Economic variables, contract conditions, tax benefits and financing arrangements (including interest rate and funding structure) were taken from official information sources and the Data Rooms[2] of the last licencing round for large-scale solar photovoltaic projects in Uruguay in 2013 [44], [45]. They are all presented and discussed in the section *Economic analysis of different configurations* in the chapter *Economic analysis*.

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[2] Data Rooms are formal meetings between the DNE and investors prior to licencing rounds, where the conditions of the calls for projects are presented and discussed.

## *3.2 Environmental assessment*

### *3.2.1 Analysis of Uruguayan regulatory framework*

The analysis of the environmental regulatory framework for solar power projects in Uruguay was conducted by reviewing the principal laws and decrees that regulate the Environmental Impact Assessment process. They are all published in the web site of DINAMA and/or in the official database of the Uruguayan Government, *IMPO Centro de Información Oficial*.

The Decree 349/005 establishes the "*Environmental Impact Assessment and Environmental Permits Regulation*", which represent the main guidelines and the central regulation for environmental matters in Uruguay. The general aspects of this decree were described in *Chapter 2 - Literature review,* while its applicability to a hybrid power plant was evaluated considering the especial characteristics of such a plant layout.

### *3.2.2 Environmental evaluation of the hybrid configuration and the case study*

The main environmental matters associated with solar photovoltaic power plants and hybrid plants were described in *Chapter 2 - Literature review.* This information was complemented and validated by professionals with experience in Environmental Impact Assessment processes in Uruguay (particularly for renewable energy projects) through consultation and interviews.

The evaluation of the case study was conducted by considering the reported impacts for solar power projects and the Uruguayan regulatory framework. In addition, the characteristics of the site were considered for the description of the environment and the identification and evaluation of impacts (eg communities, biodiversity, protected areas and natural resources).

The information was taken from the Environmental Feasibility of Location report of *Pampa* wind farm (available in the web site of DINAMA), government's reports, databases, consultation with experience professionals and information from other existing solar photovoltaic plants (also available in the web site of DINAMA).

The methodology for the identification and evaluation of impacts was based on the *European Union Guidance on EIA – Scoping* [46]. This guidance presents checklists for scoping the impacts and evaluating their significance. The process was as follows:

- Identification of potential environmental impacts of the project considering the activities or sources of impacts and the project environment.
- Evaluation of whether these impacts are likely to be significant or not by using the *Checklist of Criteria for Evaluating the Significance of Impacts*.

Finally, alternatives and mitigation measures were outlined for each significant impact by following the *Checklist of Potential Alternatives and Mitigation Measures* of the EU guidance.

# 4 Location evaluation of the case study

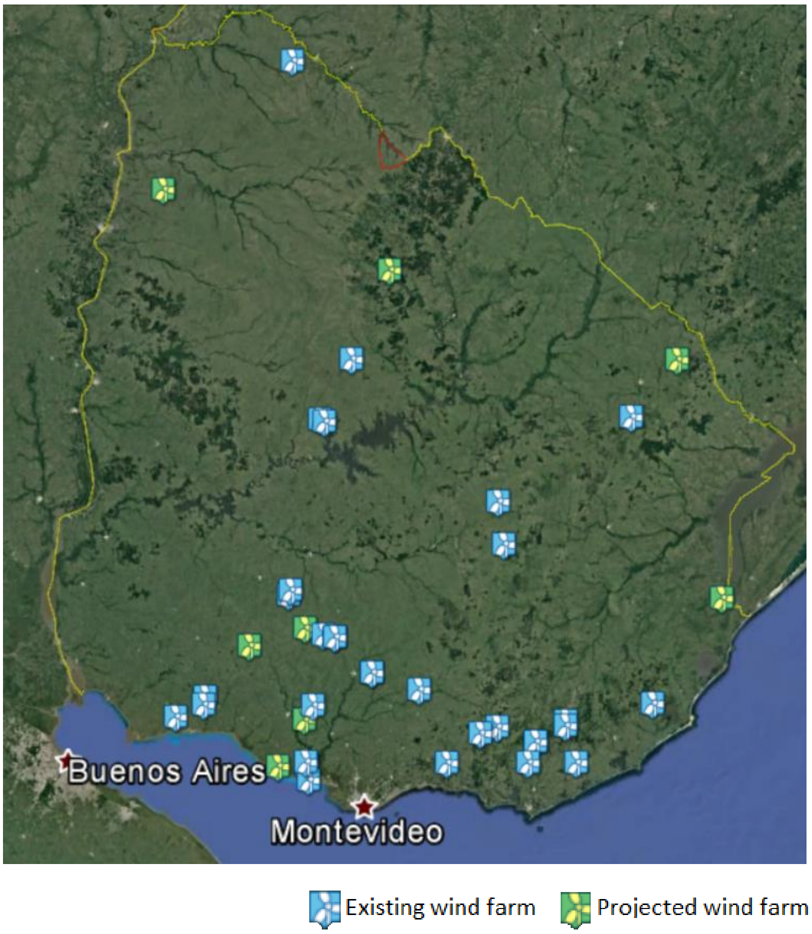
The evaluation of the site to consider for the case study depends on the existing wind farms, their characteristics (eg installed capacity, substation capacity limitation and main environmental features), the transmission and distribution systems and the solar resource in Uruguay. All this information must be analysed altogether to define the optimum location for the solar photovoltaic power plant to be installed.

## *4.1 Existing wind farms*

According to the last update of the DNE “Energy Maps”, by October 2016 there were 33 wind farms in operation stage, with a total capacity of 1,191.6 MW. The capacity of these wind farms varies between 0.2 MW to 141.6 MW, although the majority ranges between 50 MW to 70 MW.

In fact, the 141.6 MW *Pampa wind farm* (owned by UTE) is the only wind power plant that exceeds 100 MW capacity, doubling the capacity of the second largest wind power plant in Uruguay, *Valentines wind farm* [23]. The geographical distribution of the existing wind farms is shown in Figure 4—1.

**Figure 4—1 Geographical distribution of wind farms in Uruguay**

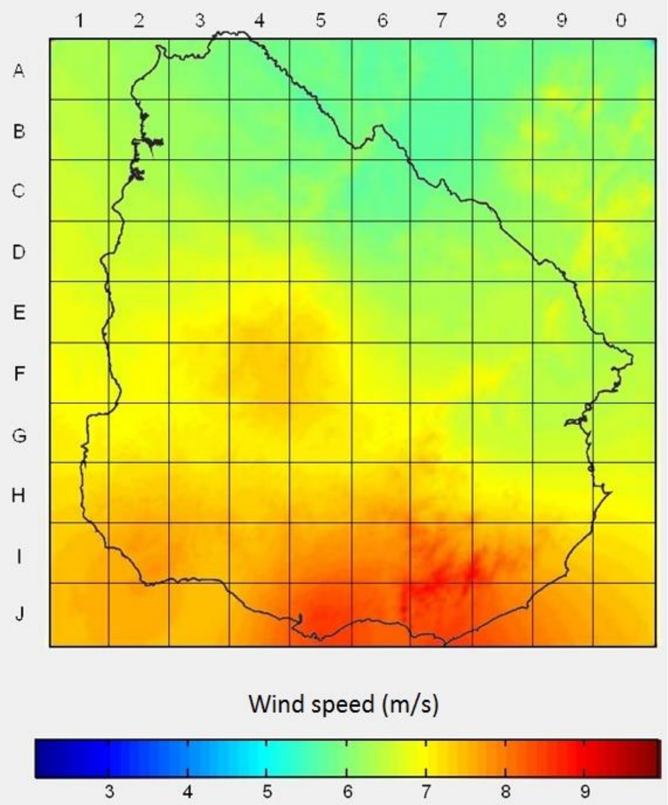


*Source: DNE [23].*

The location of the wind farms is closely related to the distribution of the wind resource in Uruguay. In this context, the annual average wind speed offers a general approximation to the best locations for wind farms within the country (even though the best locations require site-specific evaluation). As can be seen in the *Uruguay Wind Speed Map* (Figure 4—2), developed by FING-UdelaR and the DNE, the best wind resource occurs in the southeast area, and it decreases toward the north of the territory [47].

Comparing both maps, the correlation between the annual average wind speed distribution and the location of the existing and projected wind farms is clear. There is a great geographical concentration of wind power developments in the south and southeast areas, where the resource is better. In contrast, in the north of the country there are only four existing wind farms and two projected ones.

**Figure 4—2 Annual average wind speed map (90 m)**



*Source: Programa de Energía Eólica, DNE [47].*

### *4.2 Solar resource*

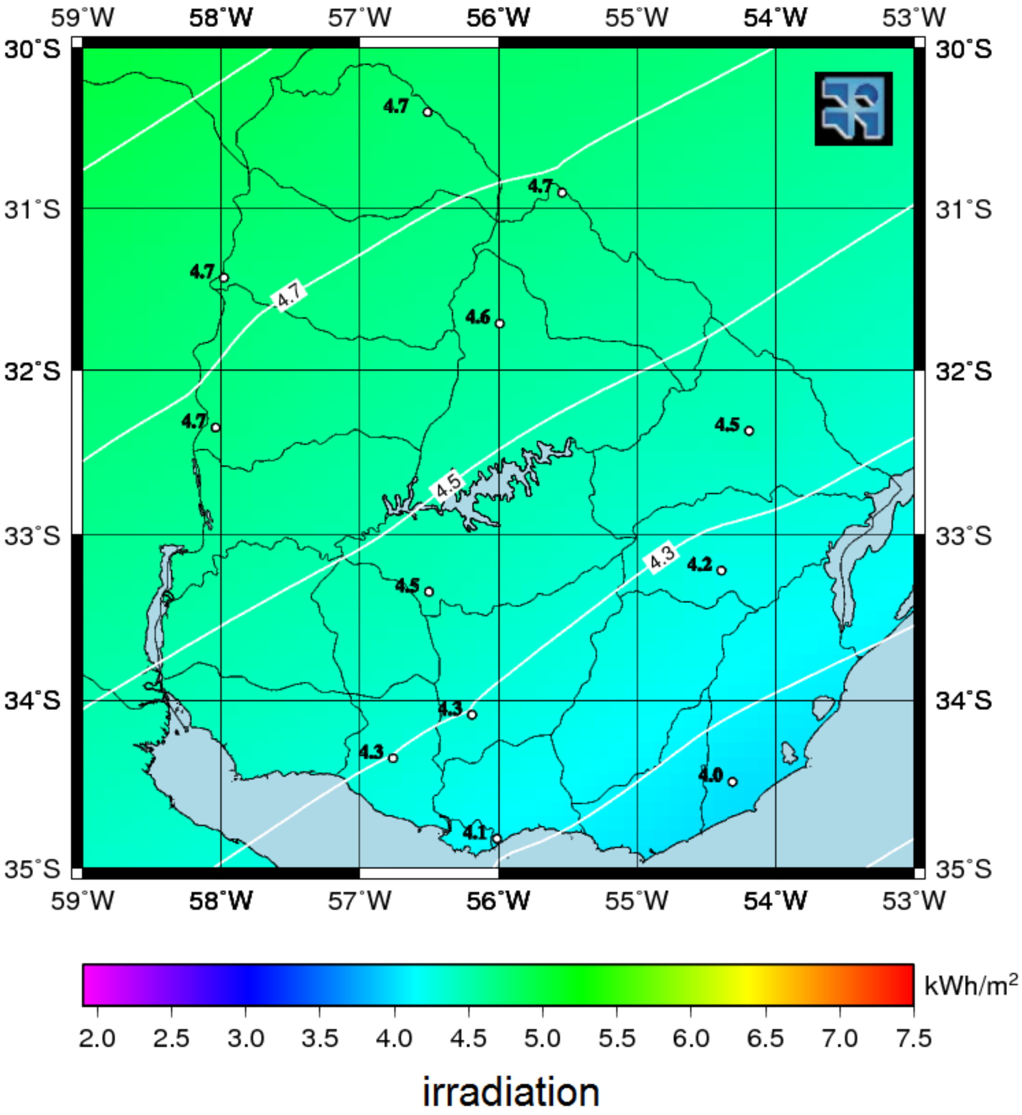
FING-UdelaR counts on a specialised unit to study the solar resource in Uruguay, LES. This unit is aimed at measuring, modelling and forecasting the resource, as well as researching prototypes for its exploitation. This laboratory has developed the first Uruguayan Solar Map and its own model based on satellite images for estimating the solar resource (average hourly and daily irradiation).

According to information from LES, it is possible to get estimate data on hourly and daily irradiation at any point of the Uruguayan territory, based on over 15-years satellite information. In addition, these data have been compared with real values from UTE and their uncertainties have been calculated as 13% and 6% for hourly and daily data respectively [48].

Being located within the sub-tropical zone, between latitude -30°06’ and -34°58’, Uruguay has a very valuable solar resource. The annual average value for daily irradiation ranges from 4.0 kWh/m$^2$/day to 4.7 kWh/m$^2$/day, increasing steadily from the southeast to the northwest of the territory [49].

The last version available of the Uruguay Solar Map is shown in Figure 4—3, where it can be observed the distribution of the solar resource over the Uruguayan territory.

**Figure 4—3 Annual average of daily irradiation values in Uruguay**



*Source: FING-UdelaR; DNE [49].*

Within a year, the daily irradiation presents a wide range of values for a single place. The highest irradiation values occur in the north and northwest during summer (December and January), while the lowest irradiation figures are recorded in the south and southeast during winter (July and August). If monthly average values are considered, daily irradiation ranges between 1.9 kWh/m$^2$/day (Atlantic coast in June) to 7.0 kWh/m$^2$/day (northwest coastline in December and January) [50]. Monthly average values of daily irradiation are presented in Figure 4—4.

Considering both annual and monthly averages of daily irradiation, the north and northwest of Uruguay are the most suitable places to develop solar energy in terms of resource availability. On an annual basis, the northwest of the country receives 17.5% more solar energy per unit area than the southeast, and between 5% to 10% more than the central regions. These differences could have relevant impacts on the economic viability of solar photovoltaic projects, given that the economic aspect is currently the main limiting factor for the development of this technology.

In contrast to the wind resource, the solar resource is virtually independent from minor geographical changes (unless the location is affected by external factors such as obstacles). The latter is particularly valid for Uruguay, whose geographical, topographical and climatological conditions are largely homogenous throughout the entire territory, mainly characterised by mildly wavy peneplains and a temperate-moderate climate [51]. As a result, the Uruguay Solar Map could be considered as an excellent input for the evaluation of the optimum location for a solar photovoltaic power plant.

### *4.3 Integrated analysis*

From the previous sections, it is clear that the solar and wind resources in Uruguay are geographically divergent. Furthermore, there is a remarkable inverse correlation between them; where the wind resource is better (southeast and south), the solar resource is poorer and vice versa. This fact is translated in an unequal geographical distribution of the power plants. Figure 4—1 showed how the wind farms are mainly placed in the southeast and south of the country. Likewise, Figure 4—5 shows how the existing and projected solar photovoltaic farms are mostly located in the north and northwest.

When evaluating possible existing wind farms to hybridise (ie adjacently install a solar photovoltaic power plant), it should be considered that the further north/northwest the wind farm is located, the best the solar resource and, consequently, the more suitable the place to install a solar power plant. As a result, in the subsequent analysis only the four wind farms located to the north of the *Río Negro* river[3] will be considered.

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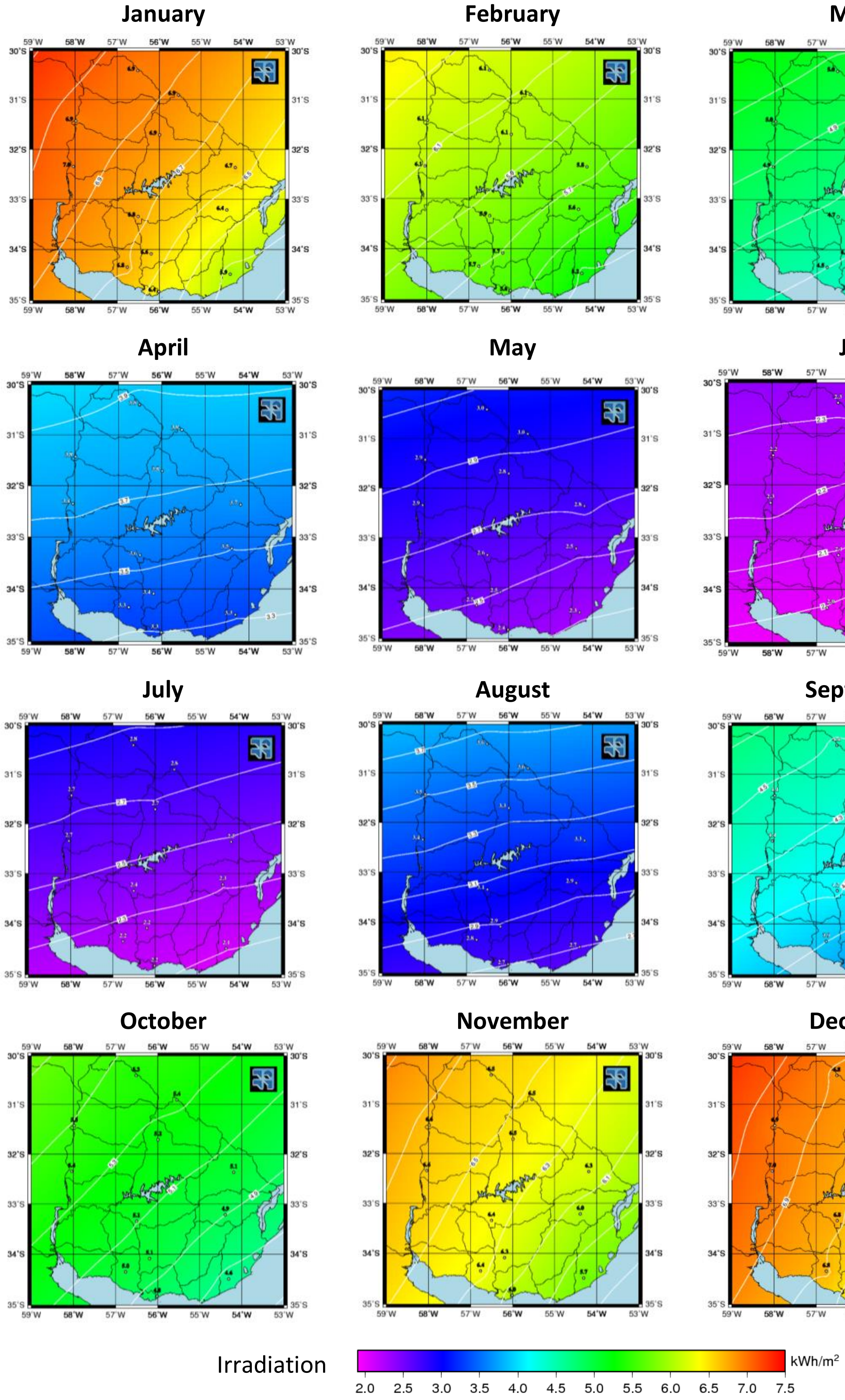
[3] *Río Negro* river crosses Uruguay from east to west, dividing the country into 2 similar-size regions (north & south).

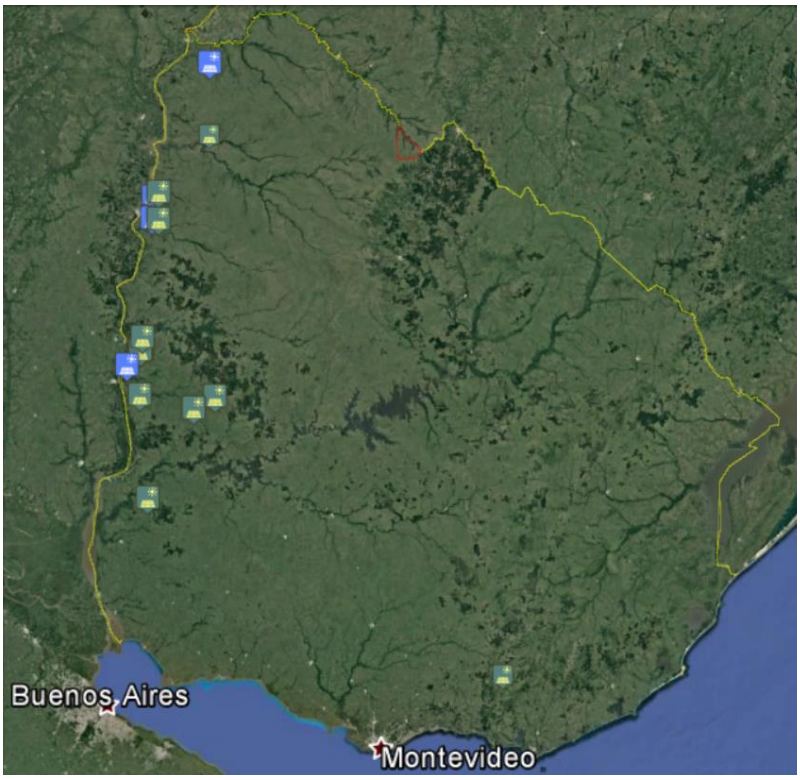
Figure 4—4 Monthly average of daily irradiation in Uruguay



January, February, March, April, May, June, July, August, September, October, November, December

Source: LES-FING-UdelaR [50].

**Figure 4—5 Geographical distribution of solar farms in Uruguay**



*Source: DNE [23].*

Existing solar farm Projected solar farm

The main features of the wind farms located to the north of the *Río Negro* river are presented in Table 4—1. All these power plants are connected to 150 kV transmission grids, and for this study, it will be assumed that the capacity of their substations and transmission systems are equal to the installed capacity of the power plants.

**Table 4—1 Main features of wind farms located to the north of *Río Negro* river**

| Wind farm | Installed capacity | Location |
|---|---|---|
| Juan Pablo Terra (UTE) | 67.2 MW |  |
| Pampa (UTE) | 141.6 MW | |
| Peralta I (Private) | 58.8 MW | |
| Peralta II (Private) | 58.8 MW | |

*Juan Pablo Terra* wind farm is located in the best site for solar energy generation within the country, with an annual average of daily irradiation of over 4.7 kWh/m$^2$/day. However, its total installed capacity is less than half the capacity of *Pampa* wind farm, which could limit the economic and environmental analysis of the hybrid solar-wind farm model.

Furthermore, considering that the difference between the solar energy received in both sites (*Juan Pablo Terra* and *Pampa*) is between 2% to 3% (4.6 kWh/m$^2$/day *vs*. 4.7 kWh/m$^2$/day), the location of *Pampa* could be considered as good as the location of *Juan Pablo Terra*. In addition, being the largest wind farm in Uruguay, *Pampa* will allow conducting more comprehensive evaluations and wider sensitivity analyses in this study. For these reasons, *Pampa* is the wind farm selected for the case study.

### *4.3.1 Pampa wind farm*

*Pampa* wind farm is owned by the financial trust *Pampa* (20% UTE and 80% retail investors) and it is placed in rented land from private landlords. The power plant is in the province of Tacuarembó, 320 km to the north of Montevideo (S 32°14’47.76”; W 56°12’54.10”).

It counts on 59 Nordex N117 wind turbines of 2.4 MW unit capacity each (141.6 MW total installed capacity), and it is connected to a 150 kV transmission grid [52], [53]. A photography of *Pampa* wind farm is shown in Figure 4—6.

**Figure 4—6 *Pampa* wind farm**

*Source: Presidencia, República Oriental del Uruguay*[4]

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[4] https://www.presidencia.gub.uy/comunicacion/comunicacionnoticias/ute-casaravilla-entrada-funcionamiento-pampa-alcanzo-mil-megavatios

# 5 Economic analysis

## *5.1 Technical alternatives for co-location of solar and wind farms in Uruguay*

Gurin *et al.* report [26] was part of an ongoing research commissioned by the DNE to study the potential of resource complementarity in Uruguay, and it had two main objectives. Firstly, it aimed at developing stochastic models of solar and wind resources along with temperature, for optimising the design of electrical systems. Secondly, it evaluated the impact of hybrid solar-wind farms on the use of the connection point to the grid, which is a key input for the present dissertation project.

From the first objective, it was concluded that coupled models of solar and wind resources produce more accurate outcomes and avoid oversized electric systems in comparison to decoupled models. The aggregated data incorporate the interrelation between both resources, taking account of their complementarity and allowing the system to reach an optimum mix with lower installed capacity.

From the second objective, the report outcomes represent the first approach to the study of the impacts of hybrid farms on the use of the grid connection point in Uruguay. The report assessed the potential of the complementarity between solar and wind power generation at the same site, including the main features of the connection to the electricity grid. Particularly, it assessed three possible scenarios:

- Installation of a solar photovoltaic farm adjacent to an existing wind farm.
- Installation of a wind farm adjacent to an existing solar photovoltaic farm.
- Optimisation of the mix solar photovoltaic and wind for new hybrid solar-wind farms.

Given the current situation of the electrical system in Uruguay, where wind power has been highly developed and the interest of the government is promoting solar photovoltaic power, the first and third scenarios are the most interesting ones.

Particularly, the first scenario will be analysed in the present dissertation project, which has the objective of assessing the economic and environmental aspects of installing a solar photovoltaic power plant adjacent to an existing wind farm in Uruguay.

Gurin *et al.* [26] developed models of wind and solar photovoltaic plants generating electricity in the same site for four locations in Uruguay. The locations were selected to represent different regions within the country, trying to include representative sites of the major areas of the territory (Atlantic coast, south-western coast, central area and north).

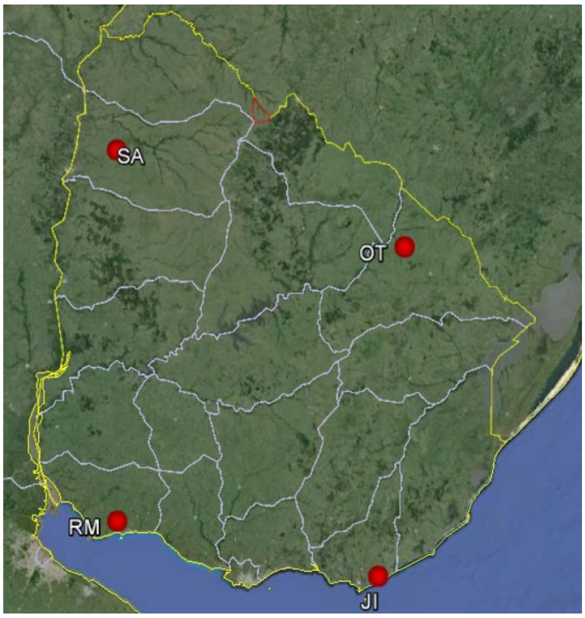
The location of the four sites are presented in Figure 5—1 and their geographic coordinates in Table 5—1.

**Table 5—1 Location of the four sites studied by Gurin *et. al***

| Code | Location | Region | UTM Coordinates | |
|---|---|---|---|---|
| JI | José Ignacio | Atlantic Coast | S 34°50’08.40” | W 54°44’09.67” |
| OT | Otamendi | Central area | S 32°07’45.49” | W 54°25’17.46” |
| RM | Rosendo Mendoza | South-west coast | S 34°19’49.43” | W 57°34’38.92” |
| SA/CR | Salto/Colonia Rubio | North | S 31°13’32.45” | W 57°27’51.65” |

*Source: Gurin et al., 2016 [26].*

**Figure 5—1 Location of the four sites studied by Gurin *et. al***



*Source: Gurin et al., 2016 [26].*

The models were run using a simulator of electrical systems created by FING-UdelaR, the *Simulador de Sistemas de Energía Eléctrica* (hereafter SimSEE). SimSEE requires data on wind speed directional distribution, solar irradiance in the horizontal plane and temperature for a specific site. It also requires the specifications of the wind and solar plants, as well as the transmission system. In terms of the solar plant specifications, the following information is needed:

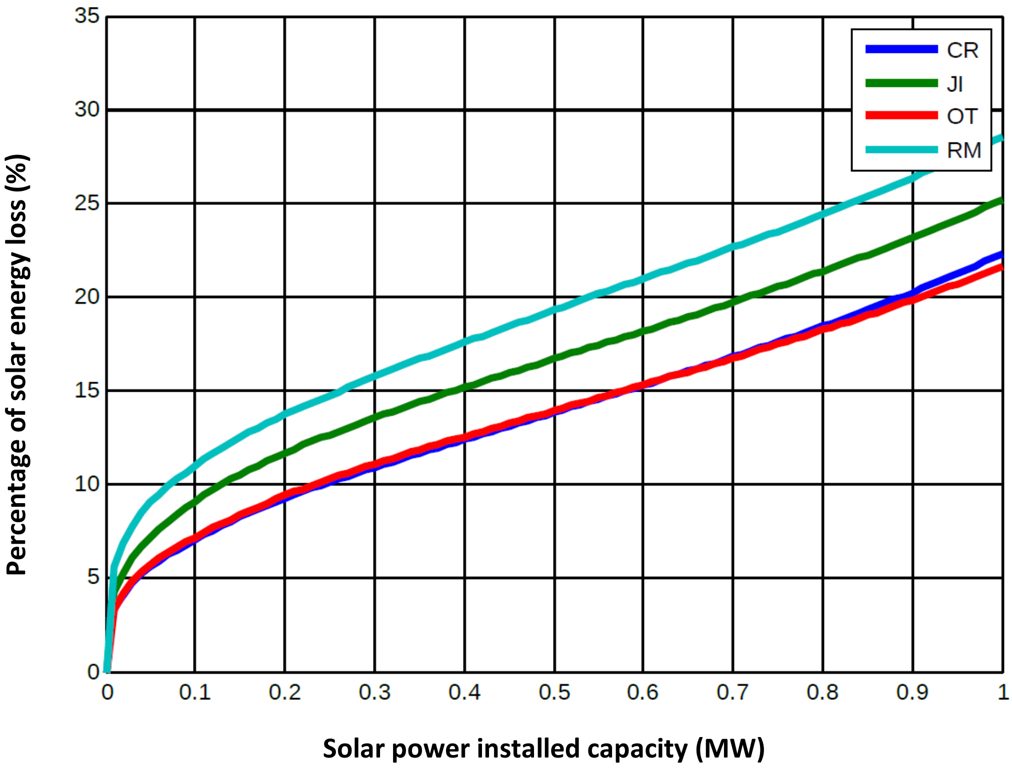
- Type and material of solar cells.
- Peak power and efficiency of the solar modules.
- Current-voltage curve (the model includes a Maximum Power Point Tracker, MPPT).
- Orientation and tilt angle of panels.
- Size of the plant (capacity).

When contrasted with a real solar photovoltaic power plant, it was found that the model underestimated the generation by 4%, so it could be assumed that the estimation represents a conservative scenario of the solar photovoltaic power generation in Uruguay.

The results were presented standardised to the unit of power of the existing wind power plant, which is assumed to be equal to its grid connection capacity. The main outcomes of the simulation were the power generated by the solar photovoltaic plant, and the share of this power that could be effectively dispatched to the grid without interfering with the transmission of wind power.

The ratio of energy loss was calculated for each of the four locations. This ratio represents the percentage of energy generated by the solar photovoltaic plant that could not be dispatched to the grid due to transmission limitations, and it is dependent on the solar power installed capacity. The results are shown in Figure 5—2.

**Figure 5—2 Energy loss vs solar power installed capacity for a hybrid farm**



*Source: Gurin et al., 2016 [26].*

The models for the four locations present similar curves of *Percentage of solar energy loss* vs. *Solar power installed capacity*, although with differences up to 10% in solar energy losses. These differences become larger at greater solar power capacities (in relation to the wind power already installed). According to this report, for SA and OT (continental territories), it would be possible to install solar power capacity up to 22% of the wind power capacity already installed with energy losses remaining below 10%.

The situation of the *Pampa* wind farm is comparable with the cases of SA and OT due to its continental location and the distance to the coastline. Thus, it could be assumed that a solar power plant installed adjacent to the *Pampa* wind farm will have a very similar *Percentage of solar energy loss* vs. *Solar power installed capacity* curve than those of SA and OT.

## *5.2 Economic analysis of different configurations*

### *5.2.1 Investment costs*

The total investment costs of solar photovoltaic projects of 10 MW, 50 MW and 100 MW in Uruguay were taken from the *KPMG* and *SEG Ingeniería* report, and they are presented in Table 5—2. This report included two possible scenarios for the development of a solar photovoltaic power plant according to the national component share of the investment, namely maximum (approximately 50%) and minimum (approximately 30%).

**Table 5—2 Total investment cost for solar photovoltaic power projects in Uruguay**

| Scenario | 10 MW | 50 MW | 100 MW |
|---|---|---|---|
| Minimum national component scenario (USD) | 17,821,201 | 90,921,417 | 174,983,405 |
| Maximum national component scenario (USD) | 18,434,030 | 93,927,067 | 181,321,410 |
| Average scenario (USD) | 18,127,616 | 92,424,242 | 178,152,408 |

*Source: KPMG and SEG Ingeniería [41].*

The average scenario was taken to conduct the cost analysis of a solar photovoltaic power plant installed adjacent to an existing wind farm. This analysis was carried out using the data for a 10 MW power plant since the capacities to be evaluated are in the range of 5 MW to 25 MW, which could be considered as small to medium scale.

The investment costs per unit of power of a solar photovoltaic power plant of less than 50 MW are presented in Table 5—3. They are divided into 18 categories as in the *KPMG* and *SEG Ingeniería* report and updated according to individual correction factors to account for the changes in technology prices between 2015 to 2017.

According to the data presented in Table 5—3, total investment costs of a solar photovoltaic project in Uruguay have decreased 32% between 2015 to 2017. This result is consistent with international reports on solar technology cost trends, which have shown reductions of 20% to 32% in the same period, according to information from the International Renewable Energy Agency (IRENA) [54].

**Table 5—3 Investment costs of a solar photovoltaic power plant (less than 50 MW)**

| Category | Cost (USD/MW) *KPMG/SEG Ing. report* | Correct. factor (ϴ) | Updated cost (USD/MW)* | Hybrid power plant | Final cost (USD/MW) |
|---|---|---|---|---|---|
| Photovoltaic modules | 770,424 | 0.60 | 458,570 | 100% | 458,570 |
| Inverters | 212,093 | 0.71 | 148,416 | 100% | 148,416 |
| Structure and manufacturer | 166,774 | 0.52 | 86,031 | 100% | 86,031 |
| Assembly and labour | 257,412 | 0.68 | 171,955 | 100% | 171,955 |
| Site preparation | 32,630 | 0.92 | 29,704 | 100% | 29,704 |
| DC wiring and interconnection | 39,881 | 0.88 | 34,787 | 100% | 34,787 |
| AC wiring and interconnection | 50,757 | 0.90 | 44,886 | 100% | 44,886 |
| Medium-voltage transformers | 21,753 | 1.04 | 22,443 | 100% | 22,443 |
| Medium-voltage line | 52,570** | n/d | 51,940*** | 0% | 0 |
| Medium-voltage substation | 106,953 | n/d | 105,670*** | 0% | 0 |
| High-voltage transformers | - | n/d | - | 0% | - |
| High-voltage lines | - | n/d | - | 0% | - |
| High-voltage substation | - | n/d | - | 10%**** | 8,052 |
| Linking-point installation | - | n/d | - | 0% | - |
| Connection/measurement point | 76,136 | 0.72 | 54,381 | 0% | 0 |
| Logistics | 25,379 | 0.90 | 22,443 | 100% | 22,443 |
| ***Subtotal*** | ***1,812,762*** | | ***1,231,226*** | | ***1,027,287*** |
| Construction insurance (0.25%) | 4,532 | - | 3,078 | 100% | 3,078 |
| Development & engineering (5%) | 90,638 | - | 61,561 | 100% | 61,561 |
| ***Total*** | ***1,907,932*** | | ***1,295,865*** | | ***1,091,926*** |

*Converted to a May 2017 based dollar rate; **4 km line; ***Assumed ϴ=1; ****Cost of adding medium-voltage switchgears (estimated as 10% of a high-voltage substation for a 50 MW power plant). n/d: no data.

*Source: KPMG and SEG Ingeniería [41].*

In terms of the benefits of installing a power plant adjacent to an existing one, the investment savings from harnessing the infrastructure were estimated in 15.7%. These estimations were made based on the opinion of experienced professionals, taking account of the investment components that would be present if a solar power plant were to be installed adjacent to an existing wind farm under the condition of this study.

Furthermore, some of the assumption made could be considered as conservatives, since some categories could apply partially (eg site preparation, insurance and development & engineering). This result is consistent with the reports of ARENA for the Australian case, where capital cost savings where estimated up to 13% [35].

### *5.2.2 Operation and maintenance costs*

The O&M costs of solar photovoltaic projects were also taken from the *KPMG* and *SEG Ingeniería* report and discussed with experienced professionals, which coincided that they have not undergone significant changes in recent years in Uruguay. As a result, they were deemed to be valid without updates (only converted at a May 2017 based dollar rate). These costs are presented in Table 5—4 for power plants of 10 MW, 50 MW and 100 MW.

**Table 5—4 O&M costs of a solar photovoltaic power plants**

| Categories | Cost (USD/year) | | |
|---|---|---|---|
| | 10 MW | 50 MW | 100 MW |
| Land rent* | 10,400 | 52,000 | 104,000 |
| Part and consumables | 33,536 | 169,321 | 332,432 |
| Salaries** | 143,976 | 277,789 | 368,126 |
| Reparations | 15,215 | 93,737 | 183,745 |
| Insurance | 42,101 | 210,265 | 413,759 |
| ***Total*** | ***245,228*** | ***803,112*** | ***1,402,063*** |
| | | | |
| Percentage of the Investment cost*** | 1.4% | 0.9% | 0.8% |
| Percentage of national component | 89.3% | 83.6% | 81.2% |

*2 ha/MW, 520 USD/ha/year; **Calculated at June 2017 values according to information from *Banco de Previsión Social del Uruguay* [55] and *Banco de la República Oriental del Uruguay*; ***Estimated 2% in the DNE's Data Rooms for 5 MW plants (2013 licencing round).

*Source: KPMG and SEG Ingeniería [41].*

From the O&M costs presented in Table 5—4, only salaries were assumed to be reduced within a hybrid power plant scheme in the range of 5 to 25 MW. The *KPMG* and *SEG Ingeniería* report considered technical staff (3), engineer (part-time), administrative staff (1) and security staff (3) working in a solar photovoltaic plant of 10 MW. Nevertheless, this approach may be considered conservative, since land rent and insurance costs could also be reduced in hybrid power plants.

According to professionals in charge of renewable energy projects in Uruguay, reductions in technical (1) and security (2) staff could be assumed if a 10 MW solar photovoltaic power plant is to be installed adjacent to an existing wind farm. The latter would produce 40% saving in salaries costs (57,590 USD/year), and therefore 23% saving in overall O&M costs. Thus, average O&M cost for a 10 MW power plant will be 18,764 USD/year per unit of power.

O&M costs per unit of power decrease as the total installed capacity increases, so they need to be adjusted for capacities above 10 MW. The adjustment for 15 MW and 25 MW was made considering a linear decrease of O&M costs in the range of 10 MW to 50 MW, using the data presented in Table 5—4.

Thus, the annual O&M costs used for the economic analysis were corrected considering the benefits of a hybrid farm configuration and adjusted according to the total installed capacity of the power plants. These values are presented in Table 5—5.

**Table 5—5 Annual O&M costs per unit of power (5 MW, 15 MW and 25 MW power plant)**

| Total installed capacity | Annual O&M costs per unit of power |
|---|---|
| 5 MW | 18,764 USD/MW |
| 15 MW | 17,973 USD/MW |
| 25 MW | 16,392 USD/MW |

### *5.2.3 Energy production and revenues*

Table 5—6 presents the expected annual energy production, the energy losses due to restriction in the transmission grid capacity and the energy dispatched for each solar power plant configuration. The revenues were then calculated as the product of the energy dispatched and the energy price for each case. The calculations of the expected annual energy production and energy dispatched are presented in *Appendix I – Energy production and energy dispatched*.

It is worth noting that the expected annual energy production presented is for the first-year operation of the plant. The efficiency of the modules is expected to drop by 3% in year two, and further 0.65% onwards as per the module manufacturer specified degradation [56].

**Table 5—6 Solar energy production for 5 MW, 15 MW and 25 MW hybrid power plants**

| | 5 MW | 15 MW | 25 MW |
|---|---|---|---|
| Energy production* ** (kWh/year) | 9,567,352 | 28,702,056 | 47,863,760 |
| Percentage of *Pampa wind farm* capacity | 3.5% | 10.6% | 17.7% |
| Energy lost rate*** | 5.0% | 7.3% | 8.9% |
| Energy dispatched (kWh/year) | 9,088,984 | 26,606,806 | 43,603,885 |

*Module Efficiency: 16.25%; Area per module: 1.9384 $m^2$; Peak power rate per module: 0.315 kW [57]. Annual average irradiation per day: 5.247 kWh/day/$m^2$ (monthly averages were used for calculations).
**Values for the first-year operation (not considering modules' efficiency loss in subsequent years)
***Gurin *et al*., 2016.

### *5.2.4 Economic and financial conditions*

The economic assessment of the different configurations of hybrid power plants was conducted based on economic data, contract conditions, tax benefits and financing arrangements (including interest rate and funding structure) taken from official information sources. The information was complemented and validated by experienced professionals in the renewable energy area in Uruguay. The data, sensitivity parameters and assumptions made were as follows:

- Economic variables
  - Discount rate: 6.7%.
  - Interest rate: 6.0%.
  - Expected inflation: 7.0% [57].
- Project costs
  - Capital cost calculated in Table 5—3. This value was taken as a sensitivity parameter for the economic evaluation, considering a variation of 10% (ie including the minimum and maximum national component scenarios).
  - Connection to the national electric system, generation licence and planning permissions are included in the capital costs, as established in the *KPMG* and *SEG Ingeniería* report.
  - Certificates of Emission Reductions (hereafter CERs) were not considered as there is no mention of carbon pricing for Uruguay in the 2016 *State and Trends of Carbon Pricing* report of the World Bank [58]. In this regard, consultation with DINAMA confirmed that commercialisation of CERs in Uruguay is not currently a common practice.

  - Renewable projects have been exempted of paying for using the electricity network and consequently, it was assumed that there will be no charges for using the network.
  - O&M average cost as presented in Table 5—5.

- Taxes
  - Electricity sales are taxed by the economic activities income tax (hereafter IRAE), which represents 25% of the total sales.
  - Law 16,909 and Decree 354/09 (regulation on investment promotions) establish an exemption of IRAE for non-conventional renewable electricity projects of 90% of the taxable net income between 2009 to 2017, 60% between 2017 to 2020 and 40% between 2020 and 2023.
  - Law 16,909 and Decree 02/12 (regulation on investment promotions) establishes an exemption of VAT and Equity tax for assets and services acquired by projects that have been promoted under the "Investment promotion and protection" Act, which includes solar photovoltaic developments.
- Financing

  Financing schemes may differ from different projects and they depend on a wide variety of external factors. However, for this study, the conditions established by the DNE in the Data Rooms for the 2013 Licencing Round for solar photovoltaic projects were assumed. These conditions are as follows:

  - Investment capital: 30% from the developers and 70% from bank loans.
  - Fixed interest rate in U.S. dollars: 7%.
  - Repayment term: 15 years, with one year of grace.
  - 100% of total investment costs are considered as depreciable assets with a lifetime of 20 years.
- Income
  - The installed capacity of the solar photovoltaic power plants and the price of the energy were taken as sensitivity parameters for the economic evaluation. These values and the different assumptions were described in section *5.2.3 Energy production and revenues.*

### 5.2.5 Economic evaluation of hybrid power plants

**Table 5—7 Economic outcomes for a 5 MW solar photovoltaic power plant**

| Percent. of calculated Investment | Energy Price (USD/MWh) | Lifetime cost (USD) | Cost/Benefit ratio | Payback period (years) | Internal Rate of Return | LCOE (USD/MWh) |
|---|---|---|---|---|---|---|
| 110% | 65 | 1,118,589 | 1.098 | - | -0.4% | 82.7 |
| | 70 | 606,141 | 1.051 | - | 2.9% | 83.1 |
| | 75 | 125,170 | 1.010 | - | 5.9% | 83.8 |
| 100% | 65 | 605,042 | 1.055 | - | 2.3% | 77.6 |
| | 70 | 122,707 | 1.011 | - | 5.8% | 78.3 |
| | 75 | -324,528 | 0.973 | 19.0 | 9.0% | 79.4 |
| 90% | 65 | 120,611 | 1.011 | - | 5.7% | 72.8 |
| | 70 | -324,223 | 0.971 | 18.1 | 9.3% | 73.9 |
| | 75 | -767,696 | 0.935 | 10.4 | 12.9% | 75.0 |

**Table 5—8 Economic outcomes for a 15 MW solar photovoltaic power plant**

| Percent. of calculated Investment | Energy Price (USD/MWh) | Lifetime cost (USD) | Cost/Benefit ratio | Payback period (years) | Internal Rate of Return | LCOE (USD/MWh) |
|---|---|---|---|---|---|---|
| 110% | 65 | 3,563,487 | 1.106 | - | -0.7% | 83.7 |
| | 70 | 2,055,664 | 1.058 | - | 2.5% | 84.1 |
| | 75 | 629,686 | 1.017 | - | 5.4% | 84.7 |
| 100% | 65 | 2,018,387 | 1.062 | - | 1.9% | 78.4 |
| | 70 | 586,932 | 1.017 | - | 5.3% | 79.1 |
| | 75 | -736,445 | 0.979 | 19.3 | 8.4% | 80.1 |
| 90% | 65 | 545,003 | 1.017 | - | 5.2% | 73.4 |
| | 70 | -767,318 | 0.977 | 19.1 | 8.8% | 74.5 |
| | 75 | -2,065,947 | 0.940 | 13.1 | 12.2% | 75.6 |

**Table 5—9 Economic outcomes for a 25 MW solar photovoltaic power plant**

| Percent. of calculated Investment | Energy Price (USD/MWh) | Lifetime cost (USD) | Cost/Benefit ratio | Payback period (years) | Internal Rate of Return | LCOE (USD/MWh) |
|---|---|---|---|---|---|---|
| 110% | 65 | 5,583,221 | 1.100 | - | 0.0% | 83.1 |
| | 70 | 3,145,291 | 1.054 | - | 3.0% | 83.6 |
| | 75 | 819,792 | 1.013 | - | 5.7% | 84.3 |
| 100% | 65 | 3,032,935 | 1.057 | - | 2.6% | 77.9 |
| | 70 | 709,597 | 1.013 | - | 5.7% | 78.5 |
| | 75 | -1,459,034 | 0.975 | 19.2 | 8.7% | 79.6 |
| 90% | 65 | 600,737 | 1.012 | - | 5.8% | 72.8 |
| | 70 | -1,548,301 | 0.972 | 18.3 | 9.1% | 73.9 |
| | 75 | -3,674,871 | 0.936 | 12.4 | 12.3% | 75.0 |

The economic outcomes of the hybrid configuration are presented in Table 5—7, Table 5—8 and Table 5—9 for the three capacities assessed. An example of the detailed calculations for one of the scenarios is presented in *Appendix II – Economic Analysis of the Hybrid Configuration.*

As mentioned before, the three different capacities were evaluated to analyse the effect of the plant size in the economic performance of the hybrid configuration (ie 5 MW, 15 MW and 25 MW). Likewise, nine different scenarios were assessed for each capacity, modifying the investment costs (ie ±10% of the estimated investment costs) and the energy price (ie 65 USD/MWh, 70 USD/MWh and 75 USD/MWh).

The comparison among different scenarios is made by comparing their IRR. The advantage of this parameter is that it allows to evaluate alternative projects rather than only mutually exclusive ones [42]. Profitable projects have IRRs higher than the interest rate, and among alternatives, the higher the IRR the more profitable the project would be.

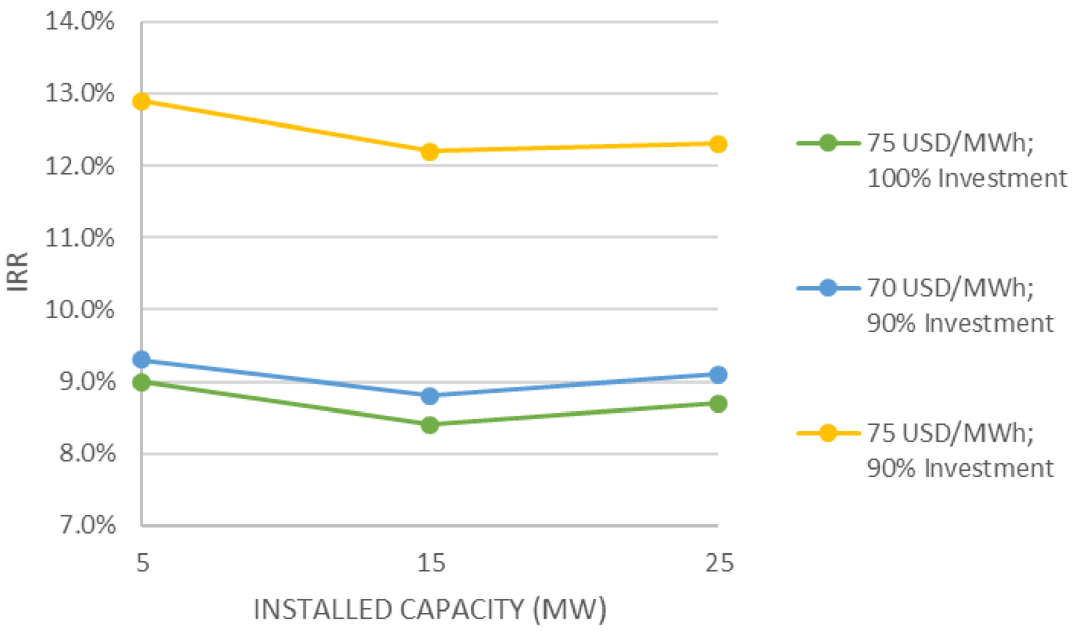
The overall results presented a similar pattern for the three capacities evaluated. Projects would only be profitable in three of the nine scenarios assessed for each capacity, and only one (ie energy price: 75 USD/MWh) if considering the investment costs as estimated in Table 5—3. When the investment costs are reduced by 10%, lower energy prices (ie 70 USD/MWh) also lead to scenarios of profitable projects. Any other scenario presented IRR lower than the interest rate, and therefore, they were not considered to be feasible under the hypothesis of this study.

In terms of installed capacity, there is no direct link between the size of the plant and the IRR of the project. Under the same conditions (same scenario), IRR decreases from 5 MW to 15 MW and then increases from 15 MW to 25 MW. According to this result, no tendency can be established between these two variables without exploring a larger number of scenarios. The economic performance of the three profitable scenarios are shown in Figure 5—3.

The main reason for this variability is the high dependency of the IRR on the Energy Lost Rate, which has a logarithmic behaviour in the range of the capacities evaluated (Figure 5—2). As a result, the outcomes of the economic performance of the different configurations are not straightforward to predict. Furthermore, they mainly depend on the energy dispatched throughout the entire lifetime of the project, which is directly link with the Energy Lost Rate. To a lesser extent, they also depend on the discount rate, the inflation, the parametric of the energy price and the life span of the project.

Due to the complex relationship between the IRR and the total installed capacity (mainly explained by the Energy Lost Rate factor for each capacity), a case-by-case study is needed to establish the optimum size of the power plant given some pre-set conditions.

**Figure 5—3 Evolution of IRR with installed capacity for profitable scenarios**



In terms of investment costs and energy prices, the economic outcomes are easily predictable. The lower the investment costs and the higher the energy prices, the higher the IRRs and therefore, the more profitable the projects. The interesting results in this regard are the threshold after which a solar photovoltaic power plant installed adjacent to an existing wind farm starts to be profitable.

Assuming an investment cost as estimated in Table 5—3 (1,091,926 USD/MW), the energy price should be between 70 USD/MWh and 75 USD/MWh for a project to start being feasible under the hypothesis of this study. This result allows to compare the hybrid configuration with the non-hybrid scenario, where a solar photovoltaic power plant is installed in the conventional way.

### *5.2.6 Economic evaluation of non-hybrid power plants*

The main value of this study is the comparison between the hybrid configuration and the conventional (non-hybrid) scenario, where a solar photovoltaic power plant is independently installed and directly connected to the grid. A comprehensive evaluation of the economic benefits of the hybrid configuration is only possible when comparing with the alternative option for developing solar photovoltaic energy in Uruguay.

The comparative analysis was made for the three capacities evaluated throughout this study at 75 USD/MWh, but only considering two scenarios of investment costs (ie 100% and 90%). The investment costs were taken from Table 5—3, but in this case, the full costs were considered (1,295,865 USD/MW).

In addition, two extra scenarios were run for each capacity. These last scenarios were conducted to determine the investment costs and the energy prices at which the same IRRs than the hybrid configuration are achieved (with all the remaining conditions unchanged).

The economic outcomes of the different non-hybrid configuration scenarios are presented in Table 5—10, Table 5—11 and Table 5—12 for 5 MW, 15 MW and 25 MW power plants respectively. The optimum investment costs and energy prices for the last two scenarios are presented in bold letters in the tables.

**Table 5—10 Economic outcomes for a 5 MW non-hybrid solar photovoltaic power plant**

| **Percent. of calculated investment** | **Energy Price (USD/MWh)** | **Lifetime cost (USD)** | **Cost/Benefit ratio** | **Payback period (years)** | **Internal Rate of Return** | **LCOE (USD/MWh)** |
|---|---|---|---|---|---|---|
| 100%* | 75 | 551,142 | 1.042 | - | 2.9% | 87.8 |
| 90%* | 75 | 19,267 | 1.002 | - | 6.5% | 82.8 |
| **80%**** | 75 | -247,787 | 0.978 | 18.1 | 9.0%*** | 80.0 |
| 100%** | **86.8** | -366,753 | 0.975 | 18.3 | 9.0%*** | 92.1 |

*Without considering the medium-voltage line. **Considering a 4-km medium-voltage-line. ***Same Internal Rate of Return that the 5 MW power plant (100% Investment; 75 USD/MWh energy price).

**Table 5—11 Economic outcomes for a 15 MW non-hybrid solar photovoltaic power plant**

| Percent. of calculated investment | Energy Price (USD/MWh) | Lifetime cost (USD) | Cost/Benefit ratio | Payback period (years) | Internal Rate of Return | LCOE (USD/MWh) |
|---|---|---|---|---|---|---|
| 100%* | 75 | 1,221,095 | 1.031 | - | 4.0% | 86.4 |
| 90%* | 75 | -341,039 | 0.991 | 21.1 | 7.6% | 81.5 |
| **83.7%**** | 75 | -662,811 | 0.982 | 19.1 | 8.4%*** | 80.5 |
| 100%** | **84.5** | -854,896 | 0.980 | 19.2 | 8.4%*** | 90.4 |

*Without considering the medium-voltage line. **Considering a 4-km medium-voltage-line. ***Same Internal Rate of Return that the 15 MW power plant (100% Investment; 75 USD/MWh energy price).

**Table 5—12 Economic outcomes for a 25 MW non-hybrid solar photovoltaic power plant**

| Percent. of calculated investment | Energy Price (USD/MWh) | Lifetime cost (USD) | Cost/Benefit ratio | Payback period (years) | Internal Rate of Return | LCOE (USD/MWh) |
|---|---|---|---|---|---|---|
| 100%* | 75 | 957,969 | 1.015 | - | 5.5% | 84.4 |
| 90%* | 75 | -1,599,752 | 0.975 | 18.3 | 9.0% | 79.6 |
| **86.5%**** | 75 | -1,429,239 | 0.977 | 19.1 | 8.7%*** | 79.9 |
| 100%** | **83.0** | -1,755,961 | 0.975 | 19.1 | 8.7%*** | 88.1 |

*Without considering the medium-voltage line. **Considering a 4-km medium-voltage-line. ***Same Internal Rate of Return that the 25 MW power plant (100% Investment; 75 USD/MWh energy price).

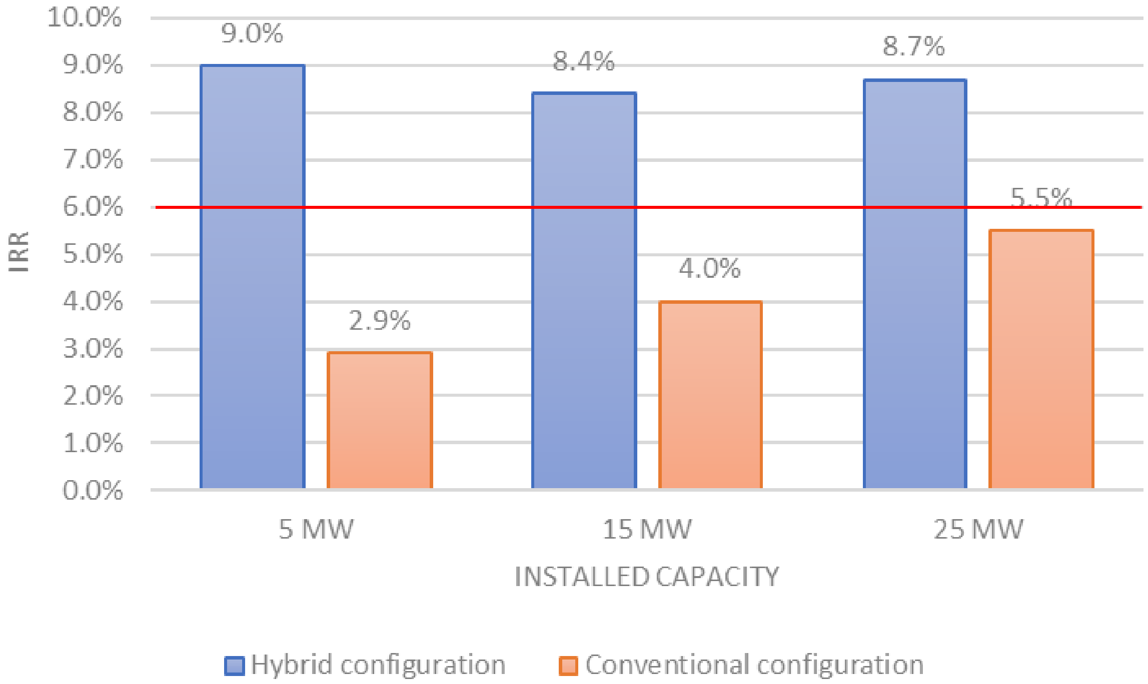
The most relevant outcome of this comparison is that any conventional (non-hybrid) project would be profitable at energy prices of 75 USD/MWh and 100% of the investment costs. Furthermore, the calculations were made without considering the costs of laying the medium-voltage line, so the costs would be even higher than those considered. In contrast, all the scenarios led to profitable projects for the hybrid configuration under the same conditions, as shown in Table 5—7, Table 5—8 and Table 5—9.

The latter is a remarkable result, showing that under the conditions and assumptions of this study, the hybrid configuration is a more feasible solution for developing solar photovoltaic energy in Uruguay. Despite the energy losses due to restrictions in the transmission grid capacity, the savings in investment costs (15.7%) and O&M costs (23%) led to more feasible alternatives.

Figure 5—4 shows the comparison of the IRRs for hybrid and conventional configurations for the three different capacities evaluated, considering an energy price of 75 USD/MWh and 100% of the investment costs. The assumed interest rate is presented in red line in Figure 5—4, setting the limit after which a project starts to be profitable.

The difference between the IRRs for hybrid and conventional configurations narrows as the solar photovoltaic capacity increases, so a hybrid power plant would be more profitable at smaller scales. At larger scales, the conventional configuration begins to be competitive. The latter could be mainly explained by the increasing energy losses as the installed capacity grows.

**Figure 5—4 Comparison of IRRs among hybrid and conventional configurations**

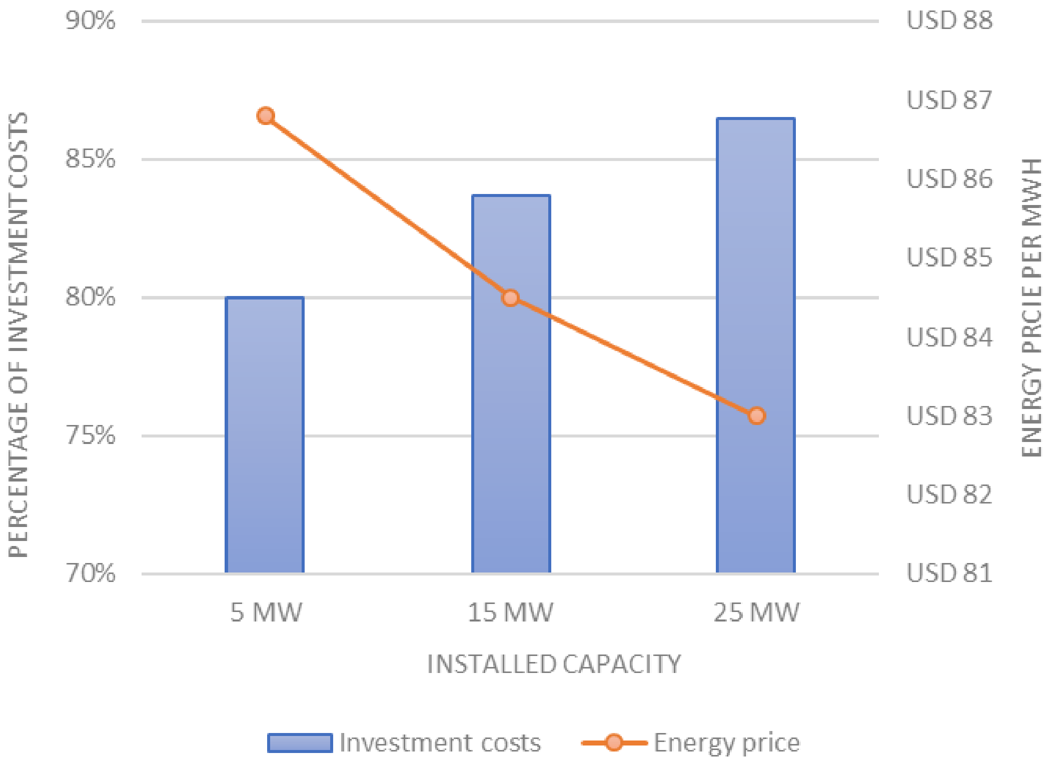


Another way to compare the hybrid and conventional configurations is by comparing the investment costs and energy prices when the IRR are equal. In this case, the IRR values of the hybrid configuration were used to determine both the optimum investment costs and the optimum energy price for the conventional configuration (with all the remaining condition unchanged). The results are presented in Table 5—10, Table 5—11 and Table 5—12.

As when comparing IRRs, the analysis of the investment costs and the energy prices shows that the conventional configuration becomes more competitive at greater installed capacities. This means higher percentage of the investment costs (lesser investment reduction required) and lower energy prices.

The total investment costs of a project must decrease 20% for 5 MW, 16.3% for 15 MW and 13.5% for 25 MW if the conventional configuration is to achieve the same economic performance as the hybrid one. Likewise, the energy prices must increase to 86.8 USD/MWh for 5 MW, 84.5 USD/MWh for 15 MW and 83.0 USD/MWh for 25 MW to obtain the same results. The latter means increases in the energy prices of 15.7%, 12.7% and 10.7% respectively. These results are shown in Figure 5—5.

**Figure 5—5 Investment costs & energy price for conventional plants (IRR as hybrid plants)**



### 5.2.7 *Discussion of results*

As explained before, the Uruguayan Government is highly interested in developing solar photovoltaic energy as a sustainable way to further expand its electrical system. The main objective is to continue diversifying the energy matrix, becoming more independent from external factors and improving its energy sovereignty. In this context, Uruguay has highly developed biomass and wind power in recent years, but solar remains being a marginal source of energy, which gives it a great potential to be expanded.

In addition, the excellent complementarity between the wind and the solar resource may allow the expansion of the electrical system to rely on the solar photovoltaic technology. However, the costs of this technology are still a major constraint and therefore, alternatives must be evaluated to bring them down.

In this study, the alternative of installing a solar photovoltaic power plant adjacent to an existing wind farm was evaluated under different scenarios. This strategy has been implemented in countries like Australia and India, where significant reductions have been achieved in investment and O&M costs [33], [34], [35]. Furthermore, this strategy may be particularly appropriate to Uruguay, where many wind power plants have been installed and the government has been especially keen on introducing renewable energies.

The outcomes of the economic analyses have shown that the hybrid configuration represents a more feasible alternative for the installation of solar photovoltaic power plants in the range of 5 MW to 25 MW. This configuration could reduce the investment costs of a solar projects by 15.7% and the O&M costs up to 23% in Uruguay.

Under the same conditions of investment costs and energy price, a solar photovoltaic power plant installed adjacent to an existing wind farm presented greater IRR than the conventional situation, which means that the former leads to more profitable projects. Furthermore, if the energy price is around 75 USD/MWh (reasonable price at current rates), the conventional configuration would not be profitable for projects under 25 MW. In contrast, the hybrid configuration would allow to achieve IRRs of 8.4% to 9.0%.

Overall, the benefits of the hybrid configuration are greater as the capacity installed decreases, which means that this solution may be better for developing small to medium scale power plants. The latter is related to the increases of energy losses as more power is installed in a hybrid configuration due to restrictions in the transmission grid capacity.

When comparing the hybrid and conventional configurations under the same economic conditions (same IRR), the benefits of the former become clear. If the investment costs of the conventional configuration are to obtain equal IRRs than those of the hybrid model, they must be reduced between 13.5% to 20.0% in the range of 5 MW to 25 MW. Likewise, for the conventional configuration to obtain equal IRRs than the hybrid configuration (considering 100% of the investment costs), the energy prices must increase between 10.7% to 15.7%.

From all the above mentioned, the hybrid configuration would be a more feasible alternative than the conventional one for developing solar photovoltaic energy in Uruguay under the conditions of this study. This outcome is especially relevant to boost the solar photovoltaic technology in the near future, since it could help to bring down the prices and make it competitive with other renewable and non-renewable technologies.

Furthermore, hybrid power plants may be the key to accelerate the introduction of the solar photovoltaic technology in Uruguay. The latter would allow the government to avoid or delay the installation of thermal back-up and energy storage systems, as well as contributing to the further diversification of the energy mix, a priority of the government in the energy sector.

# 6 Environmental assessment

## *6.1 Regulatory requirements*

The development of different renewable energy technologies may produce impacts over the environment, which in the case of solar photovoltaic power are mainly related to the construction stage and the maintenance operations. As a result, the Environmental Impact Assessment process represents a comprehensive strategy for managing projects that may have social and environmental impacts.

As mentioned before, the Decree 349/005 "*Environmental Impact Assessment and Environmental Permits Regulation*" regulates the Environmental Impact Assessment process in Uruguay and establishes mandatory permissions for projects to be developed. These permissions are the AAP and AAO, and they are both required for installing and operating a solar photovoltaic power plants.

The milestones and main activities of the different stages of a power plant project are presented in Table 6—1, according to the requirements of the Decree 349/005.

**Table 6—1 Milestones and main activities for getting DINAMA permissions**

| Stage | Milestones | Main activities |
|---|---|---|
| Planning | ■ Communication of the Project to DINAMA (Project Notice).<br>■ Environmental feasibility of location (Location evaluation).<br>■ AAP (Project documents and Environmental Impact Statement for projects categorised B or C).<br>■ Summary Environmental Report | ■ Description of the project.<br>■ Description of the environment (physical, biotic, anthropogenic).<br>■ Identification and evaluation of impacts.<br>■ Development of environmental management plans (including monitoring plans). |
| Construction | ■ AAO.<br>■ Monitoring reports related to construction. | ■ Development of environmental management plan for operation (including monitoring plan). |
| Operation | ■ AAO (re-application every 3 years)<br>■ Monitoring reports related to operation. | ■ Development of environmental performance reports and adjustment of management plans. |
| Decommission | ■ Monitoring reports related to decommission. | ■ Restoration actions. |

According to the Decree 349/005, all the milestones and main activities presented in Table 6—1 must be conducted for both a hybrid configuration or a conventional power plant. Nevertheless, if a solar photovoltaic power plant is to be installed adjacent to an existing wind farm, it is possible to link the administrative files and therefore, save both administrative costs and time.

Furthermore, some of the information and data requested by the regulatory framework would be already accessible from the existing wind farm. This would be the case of the environment description and evaluation, a critical stage in the Environmental Impact Assessment process. Likewise, monitoring campaigns may be planned and conducted for the entire hybrid plant, rather than developed for independent power plants. All these benefits of a hybrid configuration may lead to further money and time savings than those described in *Chapter 5 - Economic analysis*.

The extent and depth of the information requested for DINAMA to grant the environmental permissions depends on how the project has been categorised (A, B or C). The latter depends mainly on the nature and magnitude of the development. Previous solar photovoltaic power plants above 10 MW have been categorised as A, which means that the Environmental Impact Statement described in Figure 2—13 would not be required (only the project notice and the location evaluation are required).

## *6.2 Environment description*

The environment description of the influence area of a project is a relevant part of the Environmental Impact Assessment process. Particularly, it is a requirement when presenting the Communication of the Project to DINAMA and when applying for the AAP. It usually implies the combination of desk research (databases, reports, government's documents), field work (sampling) and data analysis. The objective is to set the environmental baseline of the area.

The hybrid configuration has a significant advantage over the conventional one if considering the importance of the environment description in the overall assessment process. Furthermore, the field work, sampling and data analysis required for the environment characterisation may be significantly minimised, leading to important cost savings.

In the case of *Pampa* wind farm, the report of the Environmental Feasibility of Location is public and available in the web site of DINAMA[5]. This report presents a comprehensive description of the physical, biotic and anthropogenic environment of the influence area. The location map of the rural lots where the wind farm is placed is presented in Figure 6—1.

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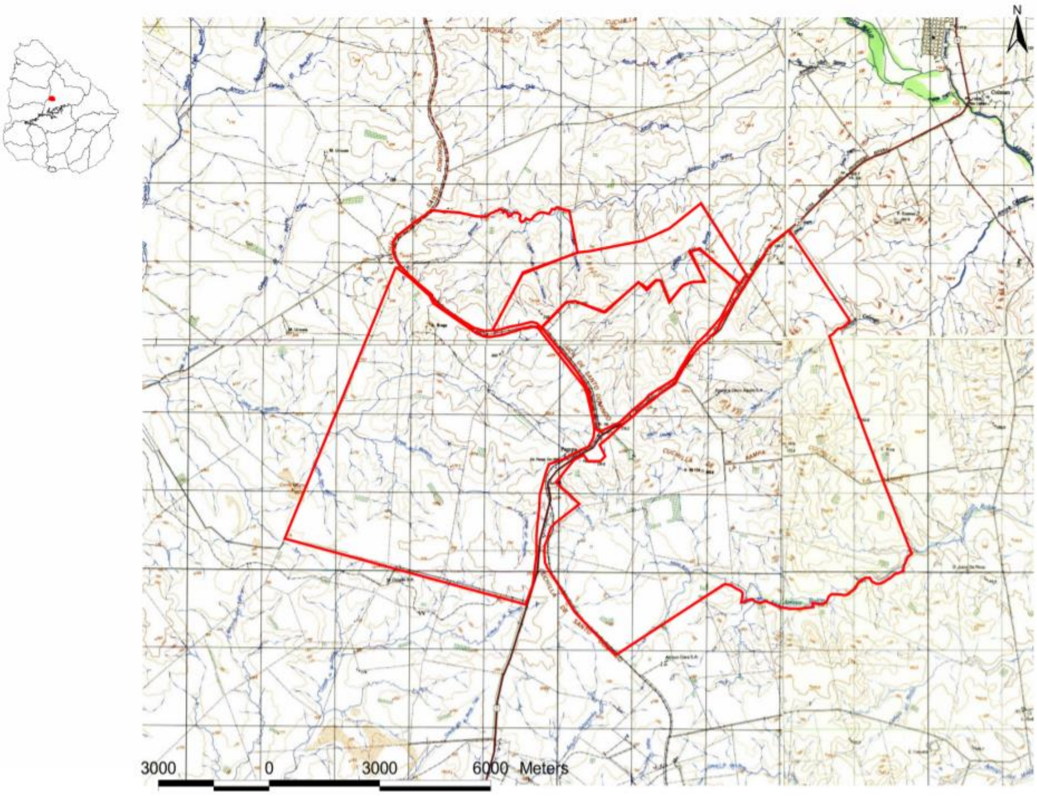
[5] http://mvotma.gub.uy/ambiente-territorio-y-agua/item/10004763-ute-parque-e%C3%B3lico-pampa-tacuaremb%C3%B3.html

**Figure 6—1 Location map of *Pampa* wind farm's rural lots**



*Source: UTE [59].*

The report of the Environmental Feasibility of Location describes the following aspects of the influence area of the *Pampa* wind farm:

- Physical environment

  Climatology (precipitations, temperatures, wind), topography, geology, soil structure and composition and hydrography.

- Biotic environment

  Ecosystems, Ecology, landscape and avifauna.

- Anthropogenic environment

  Population density, population centres (distance to the site, total population), economic activities, traffic, roads, railways and protected areas.

All this information was considered for developing the first approach to the environmental assessment of the main impacts if a solar photovoltaic power plant was to be installed adjacent to the *Pampa* wind farm.

### *6.3 Environmental Impact Assessment*

The project communication to DINAMA requires identifying and evaluating potential negative impacts over the environment, as well as outlining alternatives and mitigation measures when the impacts are deemed to be significant. Even if an Environmental Impact Statement is not required (project categorised as "A"), the impact assessment process is mandatory for getting the AAP.

For this study, the *European Union Guidance on EIA – Scoping* [46] was used to identify and evaluate the potential impacts of the hybrid project. Likewise, this guideline was used for outlining mitigation measures. During the process of environmental assessment, the Uruguayan regulatory framework was considered and the project environment description of the *Pampa* wind farm Environmental Feasibility of Location report was used.

The outcomes of the environmental impact assessment process are presented in Table 6—2.

**Table 6—2 Environmental Impact Assessment**

| **Activity** | **Impact description** | **Significance** | **Mitigation measure** |
|---|---|---|---|
| ***Construction stage*** | | | |
| Clearance of vegetation and surface soil | Potential habitat losses, landscape alteration, changes in surface runoff and erosion. | *No significant.*<br>The area to be affected would not exceed 50 ha in any case, which could be considered small for this type of projects. Furthermore, given that the solar power plant will be located adjacent to an existing wind farm, the area will be already altered.<br>In terms of surface runoff and erosion, the exposure time and affected area will be very limited (<50 ha & few months). | The time and affected area should be minimised. Likewise, the area should be re-covered by vegetation as soon as possible. |
| Workrooms installation and operation | Contamination of soil, water bodies and/or air due to construction works. | *No significant.*<br>Workrooms and storage rooms are commonly containers, so no structure would be built in the site. Containers would be brought in temporarily and remove after the construction finishes (it is a small-sized work within a very limited extension in time). | - |

| Activity | Impact description | Significance | Mitigation measure |
|---|---|---|---|
| Workrooms installation and operation | Contamination of soil, water bodies and/or air due to solid waste, liquid effluents and/or sludges from effluent treatment. | *No significant*.<br>Given the size of the work, the volumes of solid wastes and liquid effluents are expected to be limited and correctly managed (eg recycling; correct storage, transport and disposal of waste and effluents; discharge of non-contaminated effluents to water bodies after DINAMA approval). | Very simple actions of good environmental practices are required for correct storage, transport and disposal. |
| Use of vehicles & machinery | Air pollution from fuel combustion and particle matter emissions. | *No significant*.<br>The emissions would not be significant given the size of the construction work and the traffic expected. Furthermore, given that the site is in a very low-populated area, the effects of any pollutant emitted are expected to be negligible. | Optimise the traffic flow and use vehicles & machinery in good condition. |
| Use of vehicles & machinery | Increase sound pressure levels. | *Significant*.<br>Even though the area has a very low population density, noise may affect neighbours. Nevertheless, the impact would be highly limited in time and space. | Noisiest operations could be coordinated and scheduled in accordance with neighbours. |
| Storage & handling of hazardous or toxic materials | Soil, water bodies and/or air may be contaminated. Human health, fauna and flora may be affected. | *Significant*.<br>The misuse of hazardous materials (mostly oil and fuel) may have significant effects over receptors. However, the quantities are small and the operations that require handling them are simple and could be done out of site (eg refuel, maintenance). | Simple actions of good environmental practices are required for appropriately management. |
| Installation of steel structures | The installation may affect the structure of the soil. | *No significant*.<br>The structures are small and therefore, the securing operations would not significantly affect the structure of the soil. | - |

| **Activity** | **Impact description** | **Significance** | **Mitigation measure** |
|---|---|---|---|
| Laying of wires underground | The tunnelling activities may affect the soil structure. | *No significant.*<br>The wiring will be conducted at a surface levels and it would not need any additional underground structure. | - |
| Traffic (transport of personnel & materials) | Increase traffic, particularly significant at a local scale. | *Significant.*<br>During construction, the local traffic would increase significantly in comparison with the baseline (the area is very little trafficked). | Locals & workers should be informed, and signals ought to be placed in the site. |
| Use of resources | Depletion of water resources and land degradation. | *No significant.*<br>The quantities of water needed would be small and would not lead to depletion of local water resources. Likewise, the land would not suffer major alterations. | - |
| Influx of people to the area | Overdemand of local services. | *No significant.*<br>The period of the work construction would be limited to a few months, so the impact is very delimited in time. Likewise, the number of workers is expected to be small (depends on the installed capacity).<br>In terms of infrastructure, the city of Tacuarembó could easily absorb the demand for services (only 55 km away). | Services and resources may be provided from Tacuarembó or other population areas nearby. |
| ***Operation stage*** | | | |
| Presence of the power plant | Land use changes from cattle farming to power production.<br>Topography may be slightly modified to level the field. | *No significant.*<br>The area has not particular value for cattle farming, agriculture or nor any other activity (eg forestry, mining).<br>The potential changes in topography would be insignificant and would not affect surface runoff or favour erosive processes. | - |

| Activity | Impact description | Significance | Mitigation measure |
|---|---|---|---|
| Storage & handling of hazardous or toxic materials for maintenance | Soil, water bodies and/or air may be contaminated. Human health, fauna and flora may be affected. | *Significant*.<br>The misuse of hazardous materials (mostly oil and fuel) may have significant effects over receptors. However, the quantities would be highly limited (steel structures will not count on tracker systems) and the operations that require handling them would be simple (routine maintenance). | Simple measures of good environmental practices are required for appropriately management. |
| Presence of the power plant | Visual impact and effect over traffic (light reflection). | *No significant.*<br>The area where *Pampa* wind farm is placed has a very low population density and very low traffic flow. Therefore, the receptors of the impact would be few locals and occasional visitors. In addition, the area has no special landscape value. | - |
| Presence of the power plant | Biotic environment affectation. | *No significant.*<br>The small-sized plant would not affect any biological corridor (it would be in a traditionally cattle farming area). In addition, the operation of the power plant would not generate emissions or noise, so the fauna would not be disturbed. | There should be kept a vegetation coverage during the operation of the plant. |
| ***Decommissioning stage*** | | | |
| Dismantling of equipment & structures. | Increase sound pressure levels and traffic. | *No significant.*<br>The dismantling operation of the steel structures are simple and would not require major presence of machinery. In terms of noise and traffic, the impact would be very limited in time. | - |
| Dismantling of equipment & structures. | Solid waste from equipment. | *No significant*.<br>The solar modules have no hazardous material components and there are well-known alternatives for waste management. | Recycle when possible or appropriate disposal. |

The environmental assessment of the case study could be easily extrapolated to most of the solar photovoltaic projects in Uruguay. In general, this type of developments does not present critical environmental issues, and their few significant impacts are usually mitigated with simple actions. The latter may explain why DINAMA have categorised previous solar photovoltaic projects as “A”, instead of “B” or “C” which is the common situation for wind farm developments and other power generating facilities.

The construction stage of a solar photovoltaic power plant is the most critical part in terms of environmental performance. However, it is still a relatively simple construction work, built in short period of times, with delimited areas of influence and low environmental impacts.

While operating, the plant produces no noise or emissions, and its only impacts are related to the physical presence (ie visual impact, land use) and the maintenance operations (ie use of oil and other hazardous materials). Moreover, the maintenance operations are significantly reduced if the plant does not count with tracker systems, as in the case of this study.

In addition, there are some positive impacts that must also be considered in the overall impact assessment. The construction of the plant creates jobs that are mostly taken by local workforce, and it also increases the demand for services in places with low population density and non-dynamic economies (eg rural areas). In addition, the power plant contributes to continue diversifying the energy mix and generates electricity from a renewable source with low environmental impact.

If a hybrid configuration is to be included in the environmental analysis, there are two main factors that must be considered. Firstly, the cumulative impacts with the existing wind farm and secondly, the benefit of saving the construction of the transmission line.

In terms of cumulative impacts, the installation of an additional power plant will affect mainly the landscape, introducing a new element of visual intrusion. Other minor effects could be additional waste and effluents generation and further changes in land uses. However, these effects are not expected to produce significant changes to the original scenario (ie waste and effluent will not increase significantly and land use change is not commonly a relevant issue).

As explained in Table 6—2, the area of the project has very low population density and therefore, the cumulative visual impact may not be significant in this case. Furthermore, renewable energy projects have a good public perception in Uruguay and the fact that they produce jobs and revenues for the local community makes them to be well accepted within the potentially affected population.

Regarding the transmission lines, the fact that both power plants use the same infrastructure avoid their construction and thus, eliminates their environmental impacts. The main impacts of these structures are related to their construction (ie noise, increase in traffic, use of heavy machinery, safety issues, degradation of land) and their physical presence (ie alteration of landscapes, restrictions on land use, affectation of fauna, generation of electric and magnetic fields, interaction with airports and interference with radio and TV reception) [60], [61].

# 7 Conclusions

Total investment costs of solar photovoltaic projects in Uruguay decreased 32% between 2015 to 2017. In addition, the hybrid configuration could help to further reduce them by 15.7%, as well as reducing O&M costs by 23%, considering the benefits of harnessing the existing infrastructure and operating two power plants adjacently located.

Hybrid solar-wind farms in the range of 5 MW to 25 MW are feasible if the energy price is between 70 USD/MWh and 75 USD/MWh under the conditions of this study. In terms of size, there is no direct link between the capacity of the solar plant and the economic performance of the hybrid configuration, so no tendency could be defined. Because of this, a case-by-case study is needed to set the optimum size of the power plant given some pre-set conditions.

In contrast to the hybrid configuration scenarios, any conventional project would be profitable at energy prices of 75 USD/MWh, so the hybrid configuration has relevant economic benefits in comparison with the conventional one. These benefits are greater as the solar capacity installed decreases, which means that this solution may be better for developing small to medium scale power plants.

In this context, the total investment costs of a conventional project must decrease between 13.5% to 20.0% if it is to achieve the same economic performance as the hybrid configuration under the same economic conditions. Likewise, the energy prices must increase between 10.7% to 15.7% to obtain the same results.

In terms of environmental matters, the hybrid configuration could lead to significant additional money and time savings from administrative procedures, data acquisition, data analyses and monitoring campaigns.

In general, solar photovoltaic projects do not present critical environmental issues, and their few significant impacts are usually mitigated with simple actions. In this sense, if the hybrid configuration is to be included in the environmental analysis, there are two main factors that must be considered, namely the cumulative impacts with the existing wind farm and the benefit of saving the construction of the transmission lines.

Overall, the hybrid configuration is a more feasible alternative for developing solar photovoltaic energy in Uruguay under the conditions and assumptions of this study. As a result, it may represent an effective strategy to boost this technology, contributing to make it more competitive with other renewable and non-renewable options.

Furthermore, it may be the key to accelerate the introduction of the solar photovoltaic technology in Uruguay, which would allow the government to avoid or delay the installation of thermal back-up and energy storage systems, as well as contributing to the continue diversifying the energy mix. This strategy is especially appropriate to sustainably expand the energy sector in Uruguay, where many wind power plants have been installed and the government is highly interested in introducing renewable energies.

# 8 Outlooks

The conditions and assumptions made in this study have been taken from official information sources and discussed with experienced professional in the renewable energy sector in Uruguay. The information and data were reviewed and updated to get the most realistic scenarios for conducting the economic and environmental analyses. However, the energy sector is constantly changing and the variables that affect it are countless. Likewise, the scope delimits the inputs of the analyses and the scenarios evaluated.

Thus, there is still much work ahead to complete the assessment of hybrid power plants as a sustainable model for developing solar photovoltaic energy in Uruguay. From this study, some major lines of actions could be defined for further works:

- A continuous effort is needed to keep up-to-date all the information and data related with technology prices, economic aspects, financial conditions, political changes and international trends in the renewable energy sector. These factors will highly affect the outcomes of future assessments of hybrid power plants.
- The cost of the different project components will change to varying degrees and therefore, they will affect the overall assessment differently. In this context, it would be interesting to study how each component would affect the comparison between the hybrid and conventional configurations, to have an effective forecasting tool for future scenarios.
- A comprehensive analysis of the potential for co-locating wind and solar photovoltaic power plants in Uruguay would contribute to exploit the hybrid configuration as a sustainable model for the expansion of the energy sector.
- A larger number of scenarios should be run to further explore the relation between the capacity of a solar photovoltaic power plant within a hybrid configuration and the economic performance of that hybrid power plant. The better understanding of this relation will allow getting to optimised energy systems.
- Given the curves of *Percentage of solar energy los*s vs. *Solar power installed capacity* by Gurin *et al*. (2016) and the results of the present study, it would be highly interesting to analyse the economic performance of hybrid power plants with greater solar installed capacity (50 MW or more). However, this would require further detailed studies of costs, revenues and constraints, since power plants of such large capacities will need major developments and upgrades of civil and electrical infrastructure.

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## Appendix I – Energy production and energy dispatched

| **Month** | **Irradiation – Cumulative daily average (kWh/m2)** | | | | | | | | **Energy (kWh)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **2016** | **2015** | **2014** | **2013** | **2012** | **2011** | **2010** | **Average** | **5 MW** | **15 MW** | **25 MW** |
| **January** | 7.1583 | 6.5056 | 6.0972 | 7.0278 | 7.0639 | 6.7139 | 6.9889 | **6.7937** | 1,052,980.4 | 3,158,941.1 | 5,264,901.8 |
| **February** | 6.5417 | 6.8278 | 5.3667 | 6.4750 | 5.9333 | 6.6667 | 5.8361 | **6.2353** | 872,915.0 | 2,618,745.0 | 4,364,575.0 |
| **March** | 5.2028 | 6.2667 | 5.9278 | 6.3111 | 6.3583 | 6.3611 | 5.9889 | **6.0595** | 939,194.5 | 2,817,583.5 | 4,695,972.6 |
| **April** | 2.8694 | 5.6472 | 4.9972 | 5.3889 | 5.0944 | 5.0806 | 4.9694 | **4.8639** | 729,558.7 | 2,188,676.2 | 3,647,793.6 |
| **May** | 3.3444 | 4.0278 | 3.2639 | 3.3889 | 4.1583 | 4.3528 | 3.4194 | **3.7079** | 574,710.8 | 1,724,132.3 | 2,873,553.9 |
| **June** | 3.5778 | 3.8222 | 3.5222 | 3.6639 | 3.3417 | 0.4611 | 3.2167 | **3.0865** | 462,960.6 | 1,388,881.7 | 2,314,802.9 |
| **July** | 3.0194 | 3.3944 | 3.6722 | 3.5472 | 4.3361 | 3.6361 | 3.3556 | **3.5659** | 552,691.7 | 1,658,075.0 | 2,763,458.4 |
| **August** | 4.7694 | 3.5250 | 5.1278 | 4.5361 | 3.8861 | 3.8056 | 4.2611 | **4.2730** | 662,295.1 | 1,986,885.4 | 3,311,475.6 |
| **September** | 4.9528 | 4.9028 | 4.8417 | 5.4333 | 4.8389 | 5.5333 | 5.1167 | **5.0885** | 763,248.1 | 2,289,744.2 | 3,816,240.3 |
| **October** | 5.3278 | 5.1639 | 5.6083 | 6.1417 | 6.0972 | 5.5361 | 6.3222 | **5.7425** | 890,051.3 | 2,670,154.0 | 4,450,256.6 |
| **November** | 7.1333 | 5.8306 | 6.8028 | 6.2750 | 6.8611 | 7.1556 | 6.8361 | **6.6992** | 1,004,847.1 | 3,014,541.2 | 5,024,235.3 |
| **December** | 6.5806 | 6.4889 | 6.7028 | 7.4611 | 6.8472 | 7.0333 | 6.8444 | **6.8512** | 1,061,898.7 | 3,185,696.1 | 5,309,493.5 |
| | | | | | | | | ***Annual energy production*** | ***9,567,351.9*** | ***28,702,055.7*** | ***47,836,759.5*** |
| | | | | | | | | *Energy lost rate* | 5.00% | 7.27% | 8.89% |
| | | | | | | | | ***Annual energy dispatched*** | ***9,088,984.3*** | ***26,615,416.3*** | ***43,584,071.6*** |

| Installed capacity | 5 MW | 15 MW | 25 MW |
|---|---|---|---|
| N° modules* ** | 15,873 | 47,619 | 79,365 |
| Area mod. ($m^2$) | 30,768 | 92,305 | 153,841 |

*Efficiency: 16.25%; Area/module: 1.9384 $m^2$; Power rate/module: 0.315 kWp (JA Solar). **Considered AC capacity instead of DC capacity (costs already account for DC/AC losses).

# Appendix II – Economic analysis of the hybrid configuration (5 MW, 75 USD/MWh, 100% Investment)

| **Year** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Energy produced (MWh/y)* | - | 9,567.4 | 9,280.3 | 9,220.0 | 9,160.1 | 9,100.5 | 9,041.4 | 8,982.6 | 8,924.2 | 8,866.2 | 8,808.6 | 8,751.3 | 8,694.5 |
| Revenues (USD)** | - | 688,491 | 674,514 | 676,831 | 679,156 | 681,489 | 683,830 | 686,179 | 688,536 | 690,901 | 693,274 | 695,656 | 698,045 |
| O&M costs (USD)*** | - | -100,387 | -107,415 | -114,934 | -122,979 | -131,587 | -140,799 | -150,654 | -161,200 | -172,484 | -184,558 | -197,477 | -211,301 |
| **EBIDTA (USD)** | - | 588,103 | 567,100 | 561,898 | 556,177 | 549,902 | 543,031 | 535,524 | 527,336 | 518,417 | 508,716 | 498,178 | 486,745 |
| Amortization (USD) | - | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 |
| Financial cost (USD) | - | - | -267,522 | -256,876 | -245,485 | -233,296 | -220,255 | -206,300 | -191,368 | -175,392 | -158,297 | -140,005 | -120,433 |
| **Earnings before taxes (USD)** | - | 315,122 | 26,596 | 32,040 | 37,711 | 43,624 | 49,795 | 56,243 | 62,986 | 70,044 | 77,438 | 85,192 | 93,330 |
| IRAE (25%) (USD) | - | -31,512 | -2,660 | -3,204 | -5,657 | -6,544 | -7,469 | -14,061 | -15,746 | -17,511 | -19,359 | -21,298 | -23,333 |
| **Net income (USD)** | - | 283,609 | 23,937 | 28,836 | 32,054 | 37,080 | 42,326 | 42,182 | 47,239 | 52,533 | 58,078 | 63,894 | 69,998 |
| Amortization (USD) | - | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 |
| Investment (USD) | -5,459,630 | - | - | - | - | - | - | - | - | - | - | - | - |
| Loan (USD) | 3,821,741 | - | - | - | - | - | - | - | - | - | - | - | - |
| Amortization loan (USD) | - | - | -152,085 | -162,731 | -174,122 | -186,310 | -199,352 | -213,307 | -228,238 | -244,215 | -261,310 | -279,602 | -299,174 |
| **Cash flow (USD)** | -1,637,889 | 556,591 | 144,833 | 139,087 | 130,914 | 123,751 | 115,955 | 101,857 | 91,983 | 81,299 | 69,750 | 57,274 | 43,805 |
| **NPV Cash flow (USD)** | -1,637,889 | 521,641 | 127,215 | 114,497 | 101,002 | 89,480 | 78,579 | 64,690 | 54,751 | 45,353 | 36,467 | 28,064 | 20,117 |
| **Cumulative Cash flow (USD)** | -1,637,889 | -1,116,248 | -989,032 | -874,536 | -773,534 | -684,054 | -605,475 | -540,785 | -486,034 | -440,681 | -404,214 | -376,150 | -356,033 |
| NPV Costs (USD) | -5,459,630 | -123,617 | -465,249 | -442,672 | -422,975 | -403,281 | -384,827 | -371,109 | -355,086 | -340,069 | -325,994 | -312,804 | -300,444 |
| NPV Benefits (USD) | 3,821,741 | 645,258 | 592,464 | 557,169 | 523,977 | 492,761 | 463,406 | 435,799 | 409,837 | 385,422 | 362,461 | 340,868 | 320,561 |

*3% module efficiency lost the 1st year and then 0.65%/year. **Considering energy losses and energy price adjusted by UTE's parametric. ***Adjusted by 7% expected inflation.

## Appendix II – Economic analysis of the hybrid configuration (5 MW, 75 USD/MWh, 100% Investment)

| **Year** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** | **25** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Energy produced (MWh/y)* | 8,637.9 | 8,581.8 | 8,526.0 | 8,470.6 | 8,415.5 | 8,360.8 | 8,306.5 | 8,252.5 | 8,198.9 | 8,145.6 | 8,092.6 | 8,040.0 | 7,987.8 |
| Revenues (USD)** | 700,443 | 702,849 | 705,263 | 707,686 | 710,117 | 712,556 | 715,004 | 717,460 | 719,924 | 722,397 | 724,879 | 727,369 | 729,867 |
| O&M costs (USD)*** | -226,092 | -241,918 | -258,852 | -276,972 | -296,360 | -317,105 | -339,303 | -363,054 | -388,468 | -415,660 | -444,757 | -475,889 | -509,202 |
| **EBIDTA (USD)** | 474,351 | 460,931 | 446,411 | 430,714 | 413,757 | 395,451 | 375,701 | 354,406 | 331,457 | 306,737 | 280,122 | 251,479 | 220,665 |
| Amortization (USD) | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | -272,982 | - | - | - | - | - |
| Financial cost (USD) | -99,491 | -77,083 | -53,106 | -27,451 | - | - | - | - | - | - | - | - | - |
| **Earnings before taxes (USD)** | 101,879 | 110,867 | 120,324 | 130,281 | 140,775 | 122,469 | 102,720 | 81,424 | 331,457 | 306,737 | 280,122 | 251,479 | 220,665 |
| IRAE (25%) (USD) | -25,470 | -27,717 | -30,081 | -32,570 | -35,194 | -30,617 | -25,680 | -20,356 | -82,864 | -76,684 | -70,031 | -62,870 | -55,166 |
| **Net income (USD)** | 76,409 | 83,150 | 90,243 | 97,711 | 105,581 | 91,852 | 77,040 | 61,068 | 248,592 | 230,053 | 210,092 | 188,609 | 165,499 |
| Amortization (USD) | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | 272,982 | - | - | - | - | - |
| Investment (USD) | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Loan (USD) | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Amortization loan (USD) | -320,116 | -342,524 | -366,501 | -392,156 | - | - | - | - | - | - | - | - | - |
| **Cash flow (USD)** | 29,275 | 13,608 | -3,277 | -21,463 | 378,563 | 364,833 | 350,021 | 334,050 | 248,592 | 230,053 | 210,092 | 188,609 | 165,499 |
| **NPV Cash flow (USD)** | 12,600 | 5,489 | -1,239 | -7,604 | 125,702 | 113,536 | 102,087 | 91,311 | 63,685 | 55,234 | 47,274 | 39,776 | 32,710 |
| **Cumulative Cash flow (USD)** | -343,434 | -337,945 | -339,183 | -346,788 | -221,086 | -107,549 | -5,462 | 85,849 | 149,534 | 204,768 | 252,042 | 291,818 | 324,528 |
| NPV Costs (USD) | -288,864 | -278,016 | -267,854 | -258,336 | -110,093 | -108,211 | -106,451 | -104,803 | -120,746 | -118,209 | -115,837 | -113,618 | -111,545 |
| NPV Benefits (USD) | 301,464 | 283,505 | 266,615 | 250,732 | 235,795 | 221,748 | 208,538 | 196,114 | 184,431 | 173,444 | 163,111 | 153,394 | 144,256 |

*3% module efficiency lost the 1st year and then 0.65%/year. **Considering energy losses and energy price adjusted by UTE's parametric. ***Adjusted by 7% expected inflation.

## Appendix II – Economic analysis of the hybrid configuration (5 MW, 75 USD/MWh, 100% Investment)

| **Technical and economic variables** | |
|---|---|
| Interest rate | 6.0% |
| Discount rate | 6.7% |
| Investment costs (USD/MW) | 1,091,926 |
| O&M costs (USD/MW/year) | 18,764 |
| Amortization (USD/year) | 272,982 |
| Assets depreciation period (years) | 20 |
| Capacity installed (% *Pampa* capacity) | 5 MW (3.5%) |
| Energy Lost Rate | 5.0% |
| Inflation | 7.0% |
| Energy Price (USD/MWh) | 75.0 |

| **ECONOMIC OUTCOMES** | |
|---|---|
| **Net Lifetime Cost (USD)** | -324,528 |
| **Cost/Benefit Ratio** | 0.973 |
| **Payback Period (years)** | 19.0 |
| **Internal Rate of Return** | 9.0% |
| **Levelized Cost of Energy (USD/MWh)** | 79.4 |

**Financing plan** (7% annual interest; 15 years repayment period)

| Year | Loan Debt (USD) | Payment (USD) | Interest (USD) | Amortization (USD) |
|---|---|---|---|---|
| 1 | Year of grace | Year of grace | Year of grace | Year of grace |
| 2 | 3,821,741.0 | 419,606.6 | 267,521.9 | 152,084.7 |
| 3 | 3,669,656.3 | 419,606.6 | 256,875.9 | 162,730.7 |
| 4 | 3,506,925.6 | 419,606.6 | 245,484.8 | 174,121.8 |
| 5 | 3,332,803.7 | 419,606.6 | 233,296.3 | 186,310.4 |
| 6 | 3,146,493.4 | 419,606.6 | 220,254.5 | 199,352.1 |
| 7 | 2,947,141.3 | 419,606.6 | 206,299.9 | 213,306.7 |
| 8 | 2,733,834.6 | 419,606.6 | 191,368.4 | 228,238.2 |
| 9 | 2,505,596.4 | 419,606.6 | 175,391.7 | 244,214.9 |
| 10 | 2,261,381.5 | 419,606.6 | 158,296.7 | 261,309.9 |
| 11 | 2,000,071.6 | 419,606.6 | 140,005.0 | 279,601.6 |
| 12 | 1,720,470.0 | 419,606.6 | 120,432.9 | 299,173.7 |
| 13 | 1,421,296.3 | 419,606.6 | 99,490.7 | 320,115.9 |
| 14 | 1,101,180.4 | 419,606.6 | 77,082.6 | 342,524.0 |
| 15 | 758,656.4 | 419,606.6 | 53,105.9 | 366,500.7 |
| 16 | 392,155.7 | 419,606.6 | 27,450.9 | 392,155.7 |