Modeling and Optimization of the Portuguese Electricity System with Regional Disaggregation

Nuno Celestino*

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*Department of Mechanical Engineering, Instituto Superior Técnico, University of Lisbon (ULisbon)
Av. Rovisco Pais, 1049-001 Lisboa, Portugal
e-mail: nuno.celestino@tecnico.ulisboa.pt

Abstract
This work includes a study of energy planning with high spatial and temporal resolution, which integrates the high dynamics of the electrical system, considering the hourly variations in demand and production and analyses the existing potential in each of the considered regions, in order to increase future production levels. It is considered the need for a high penetration of renewable energy-based technologies, when it is expected that the electric sector reaches an almost total decarbonisation by 2050.

The analysis shows that the deployment of renewables, allows Portugal to be an exporter in medium-long term, considering the Iberian electricity system. The technical limits for the installed capacity directly influence the installation of new power plants, once a particular RES technology is implemented as a function of some other capacity saturation. This has a direct impact on the electricity sector costs, leading the system to choose more efficient technologies in order to increase productivity at constant capacity, given the need to supply, which contributed to the steady rise in costs over time. It also appears that, a breakdown implementation allows a significant reduction in rising mitigation costs in the medium term, and a larger export volume, when compared with this methodology absence.

Keywords: Base line scenarios, bottom-up energy modeling, capacity factor, energy policy, renewable based technologies, supply side analysis.

1. Introduction
Throughout the industrial revolution, energy consumption from fossil fuels has been the engine behind the industrialized world and economic growth. The production of energy from such sources has grown from negligible levels in the early 19th century, and, in 2010 these fuels had an output of about 10 000 million tonnes of oil equivalent (toe) [16]. However, this same revolution led to a large-scale technological advance over the last century and up to today, giving us the chance to look closest at the energy planning. In particular, the increase of technologies for the electricity generation from Renewable Energy Sources (RES), whose applicability fields are increasing as their efficiency. Fossil fuels, particularly petroleum, coal and natural gas (NG), represent an environmental threat, being responsible for the emission of Greenhouse Gases (GHG).

According to [19], since 1850 the average global temperature has increased by 0.7 °C, and it is predicted that, this may increase over 4 °C until the end of the century, if emissions of such gases continue to grow up. In 2010, 43% of all carbon dioxide (CO₂) emissions provided from coal, 36% from oil and 20% from gas [17].

Studies focused on a mitigation policies implementation refer to exist a need to improve them, widening the scope of national efforts. This because, despite the various implemented policies, the existence of the Framework UN Convention on Climate Change (UNFCCC) and the Kyoto Protocol, the growth rate of GHG emissions in the recent decade (2000-2010) reached values about twice as to any other, since 1970 [18].

It is estimated that energy demand will increase by about 40% over the next 20 years, initially in developing countries [31]. Thus, and if it does not adopt the necessary measures, this increase in consumption reinforces the idea of a continuous growth of CO₂ emissions in the future, as Figure 1 suggests, and in which the electricity sector, in particular, is responsible for more than 40%.
The European energy system is currently facing many uncertainties: the high unpredictability in the price of fossil fuels and the resulting of economic and geopolitical risks, inherent to the dependence on imports challenges as well as adverse environmental impacts associated with electricity generation based on fossil fuels [11]. Therefore, it becomes necessary to adopt alternatives and policies that result in increased levels of sustainability for the energy sector, both in economic and environmental component, while ensuring a security of supply.

This work fits in the energy planning context, built on the slope of the electric sector. It is intended, primarily, to extend the rational component in energy production, optimizing the use of renewable energy available, as a way of making future investments in such markets (technologies for electricity generation), while ensuring the minimization of surplus production, safety supply and lower cost implementation of new technologies.

Thus, it is expected a continuous growth for a future sustainability, based on an environmental perspective.

**Objectives**

In general, this study aims to determine strategies for future planning by 2050, leading to increased national energy sustainability for the electricity sector. In the environmental field, and for this horizon, it is intended to achieve a reduction on GHG emissions for the electricity sector by about 96%, compared to 1990 levels, in line with the targets set by the European Union (EU).

Considering a different scenarios adoption, starting with analysis of each of the regions as a fraction, and imposing limits on GHG emissions, it is intend to find new ways for a global planning (i.e., for mainland Portugal).

More specifically:

- To get a better use of the existing level of RES regional potential at the production level, such as:
  - To increase production levels while reducing both fossil fuels dependence and GHG emissions;
  - To monetize the investment and enable this type of market, and consequently an increase in terms of future sustainability;
  - To reduce the dependency on electricity imports and increase exports;
- To predict the future Installed Capacity (IC) and generation distribution at the geographical level;
- To recognize the existing energy flow (ie, amount of EE exchanged between different regions), in order to plan future interventions at the level of regional sustainability;
- To calculate the costs of mitigation inherent to the GHG reduction emissions in line with international policies currently in force.

**Methodology**

It is intended to adopt a methodology of high resolution, both in spatial and temporal field.

This increasing the resolution aims to equip the model in greater detail information at the geographic level of the information, like the existing demand as the Capacity Factor (CF) for the RES.

In order to optimize the management of production and consumption and given the dynamics of the electrical system, it is also imperative to estimate both these magnitudes at higher temporal resolutions to those commonly available (annual average). This considers demand and production and production schedules in characteristic days, for different sectors (such as: Residential, Industrial and Commerce and Services), as the technologies for electricity production, based on RES.

**2. Spatial Resolution**

As is well known, different regions are distinguished by different amounts of consumption as well as by distinct existing resource levels and climatic characteristics, among other.

For the total consumption, this difference can be partly explained by the difference in recorded values for the number of inhabitants in each of the regions considered, as well as the demand distribution for each of the different sectors.

Spatial models are fitted with input data, specific to the geographical level [30]. Being that the approach, include a breakdown under a regional scope, which translates into an increase of the spatial resolution for the case study.

The implementation of a breakdown, aims to geographically identify the use and production of electricity, [22]. Thus it is possible to estimate the potential for the electricity production from renewables (particularly wind, hydro and solar), either in the climate context, both in material resources, as well as knowing the geographic distribution of demand. We intend to find the global lowest cost associated with the generation technologies for electricity production, while ensuring an adequate response to the needs, imposed by demand.

More recently the [31] study also introduces a multi-regional model for the Canadian energy system. Housed in a 2050 time horizon, it intended to maintain a high level of detail database, considering a reference disaggregation scenario. The latter, corresponding to a high/low prices for fossil fuels, and a fast/slow trend for the socio-economic growth.

Values for the IC, production, and demand of electricity, for each of the considered regions are included. The model (see section 4) is well fitted with an increase in information density, with respect to a geographical factor, so, it is expected to take a greater advantage on the available resources use.

Making an analogy to the finite elements, we could compare this increase, in spatial resolution, to a mesh in question refinement.

**2.2. Temporal Resolution**

To meet all the demand, it is necessary to maintain production levels higher than those of consumption. However, electricity should not be significantly greater than that which is consumed, once and considering the lack of provision for the storage of surplus production, that result in increased production costs [2].

[13] states that, due to its nature, there is a variation in the availability of natural resources at various time scales, from seconds to decades, with more or less relevant depending on the RES to which they relate, characterizing, qualitatively, the renewable resources dynamics.
This time, and in order to achieve a temporal resolution increasing, it is necessary to estimate both the amount of electricity demand and production at lower time periods than those normally available. The reference values for these quantities (and in most cases) presents an annual average, however, it is necessary to estimate these variations for a shorter time periods. These, are obtained in a statistical way, based on estimates by origin on the evolution the profiles for one year period. More specifically, this method implements a quantity corresponding to periods of one hour temporal resolution period.

[22] highlights the importance of implementing a temporal resolution in a planning study, as a way to simulate the electrical system dynamics, by analysing the load variation over each period.

Since, for most renewables, both demand and production depend largely on climatic factors, it is necessary to estimate these values for each of the four seasons. Taking as an example; the needs for cooling/heating as well as some of the intermittency associated with renewable energy, with respect to consumption and production respectively. For the demand particular case, there is a weekly variability, when comparing week to the weekend days, once it shows a different behaviour for each of the different activity sectors.

The methods currently used are not the most appropriate, considering the modelling of long-term scenarios for the hourly dynamics existing between production and demand [24]. So, it should be considered a dynamic supply and a seasonal daily demand. Study [25] is also based on the same methodology in order to find alternatives that lead to a high penetration of RES in the electricity system.

![Figure 2 - Hourly Electricity generation in a typical spring day](image)

![Figure 3 - Hourly electricity demand in a typical spring day](image)

Accordingly, and given to each of the considered technologies and activity sectors, are used the following schedule profiles for each season, regarding electricity generation and demand, respectively:
- Typical Weekday;
- Saturday;
- Sunday.

Indeed, to demand we obtain a total of 12 reference days, corresponding to a 12x24=288 distinct hourly periods through the year with a total of 24x365=8760. By the other hand, demand only verifies 4x24=96 distinct periods once its profile does not vary among the week days. Since the fraction corresponding to each of these periods for a time interval of one year is different, it should be weighed in the overall contribution.

The consumption analysis by sector given the use of different demand curves, relates to the existing distinct weights for each sector to be present in full consumption, when considering different regions (Figure 8).

3. Case Study – Mainland Portugal

It is considered for this study, a regional breakdown (continental Portugal) at district level, so, we obtain 18 distinct regions, each one corresponding to a district.

Then, the adopted nomenclature for each of the regions is showed, as well as the location and geographical distribution of the same (Figure 4).

Portugal is a limited country concerning the availability of the most common sources of energy, Non-Renewable Energy Sources (NRES). So far, the country has no indigenous fossil resources or enough purchase of primary energy to influence market prices (price taker) [26]. [20] refers to as a basis for other jobs which offer wider possibilities in the electricity supply in Portugal, which holds potential resources in the renewable energy sources field, with particular emphasis on intermittent, as waves, solar, wind and oceans.

This chapter contemplates IC values, generation and demand for mainland Portugal at the regional level, where, for Spain, these quantities were obtained using through the model used in [1]. For the purpose of electricity exchanging, associated to the Iberian Market of Electricity (MIBEL), we consider all interconnected adjacent regions and also links to Spain, however, the latter, with limited load.

3.1 Renewable Energy Sources

Particularly, the country has a relatively dense river network, as well as a high average annual sun exposure. Benefits from the Atlantic winds and also has an extensive maritime boundary, considering, respectively, hydropower, PV, wind and ocean, technologies for electricity generation.
These conditions allow the country to get an advantage in RES, which represents an alternative to fossil fuels use, without consequences at the level of GHG emissions. Thus, Portugal has the conditions to offset the natural NRES deficit and, hence, cater to a reduction of both GHG emissions and external energy dependence, associated with this type of sources.

Given a better use of resources and a consequent generation increase, it is also expected a better cost-benefit ratio, related to the new technologies implementation, which use this type of sources, leading, thus, to a better use of them.

There has been broad incentives in Portugal, in order to incentive penetration of these technologies, gave a country’s favorable location for its use [14].

### 3.1.1. Installed Capacity

Considering the adopted methodology, there is a need to know this same trend, not only by type of technology, but also at regional level, for each of the listed districts.

Figure 5 provides data from existing IC in each district for the technologies of RES in late 2012 [6].

![Figure 5 - Installed Capacity (year 2012)](image)

Where it is visible that different regions have a distinct capacity amount related to the mentioned technologies, as we will see then for the generation (Figure 6).

### 3.1.2. Electricity generation

The prior knowledge of the historical demand evolution alongside to the existing capacity in geographical and technological terms, leads us to estimate the existing potential in each region. Therefore, it is possible to conclude about the most appropriate region where to install a certain power plant, in order to maximize the generation rates.

![Figure 6 - Electricity production (year 2012)](image)

### 3.1.3. Capacity Factor

Renewables resources, particularly wind and solar, hold a generation capacity that directly relates to the existing climatic conditions, and therefore, has certain variability with time. Each of the regions under study is also distinguished by different climate conditions, so, it becomes necessary to estimate the average production amount in each source and region, given a reference period, as a way to estimate the existing potential for a certain RES.

This estimate is effected by means of a CF, which is obtained as a ratio between the following quantities.

\[
CF = \frac{\text{produced energy through } \Delta t}{\text{installed capacity } \times \Delta t} \tag{1}
\]

Where \( \Delta t \) is the time interval considered for the calculation.

Thus, and known values of production and/or existing potential in each region, is geographically possible to conclude about the installation of new technology as a way to optimize the produced quantity.

![Figure 7 - Regional average annual Capacity Factor](image)

It is visible the variability for this value between the different regions for the mentioned technologies, for which values are recorded between 9 and 40% approximately.

Particularly for the solar power, the low number of installations operating with this type of technologies, combined with a very significant growth rate, leading to a need to estimate the solar CF of each region by using alternative means. Thus, resorted to the Geographical Information System Photovoltaic PVGIS\(^1\). For the offshore wind CF, its assumed a value 1,5 times greater than the onshore one [29].

The CF for the concentrated solar was calculated based on solar Photovoltaic (PV) and pondered with both this technologies generation profiles.

### 3.2 Non-Renewable Energy Sources

As regards, the energy provided by this type of sources, Portugal has a set of thermal power plants, whose fuel is exclusively natural gas (NG), coal and fuel oil, and in which is concentrated all the transformation of energy from NRES into electricity. These plants are thus responsible for the remaining fraction of the complementary IC, with respect to the total capacity.

For the purpose of data processing, the core that also feature generation for forest residues, it is considered only biomass

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\(^1\) See more at: [http://re.jrc.ec.europa.eu/pvgis](http://re.jrc.ec.europa.eu/pvgis)
plants, since it ignores the fraction of IC operating with each fuel.

If some of the regions do not show the sustainable level of RES (and part of the new power of RES), it is predictable a sharing of electricity between these regions and the remaining ones, in which occur higher levels of sustainability (see Figure 10).

For this power plants, information on the type of used fuel and the overall performance is all-important, since we can conclude about the CO₂ emissions and, the monetary cost per unit of produced energy, wherein, the environmental components and economic concerns.

3.3 Demand

The knowledge for the demand evolution as a means of estimating future demand, are, from the point of view of energy planning, extremely important, since they allow to establish future production levels.

In order to provide the requested dynamics of the request for demand over time and, in particular, along each characteristic day, the need arises to ungroup the same in different sectors.

Each of these is distinguished, not only by different levels of demand, as a different seasonality (i.e., since for each sector, the power demand takes different values over a typical through a different year periods). As noted in section 3, the used methodology owns this temporal variability, which is considered as typical for the following sectors:

- Domestic;
- Industry;
- Commerce and Services.

The average demand values by sector can be observed in Figure 8 for each of the regions, between 2005 and 2012 inclusive. This figure also shows total district contribution across overall demand, that, in this period, shows an average value of about 47,15 TWh.

![Figure 8 - Average demand by activity sector (years: 2005 to 2012) [5]](image)

It is visible the difference between the demand and the relative weight to each of the sectors (in particularly for the industrial sector) in different regions. What can be, partly explained, by the geographic population distribution and the industry mobilization to specific regions.

3.3.1 Evolution Approach

Given the aforementioned need to estimate future demand and by reference to demand data available for the sectors mentioned, between 1997 and 2012 (Source: DGEG), leads to the estimate, presented in Figure 9.

![Figure 9 - Estimated future demand](image)

Apart from the last six years, in which demand shows a somewhat different behavior, a growing trend is visible for the three sectors, and hence, for the total demand. Thus, and by carrying out a linear analysis, it is expected that this same demand will continue to strive for the average increase recorded. Thus, the made estimate was based on a linear regression, calculating the expected evolution values for both sectors and regions by 2050.

3.2.1 Regional Sustainability

Once known demand values, it is possible to analyse sustainability indexes for each of the regions, which relate directly to the local productive potential, given the existing demand. It was defined as the ratio between production originating from renewable energy and the consumption of raw electricity, verified (Source: DGEG).

With particular emphasis on production originating from renewable energy, Figure 10 illustrates regional sustainability levels, considering the both real and theoretical values:

![Figure 10 – Regional RES sustainability indexes (year 2012)](image)

Regional RES sustainability was defined as the ratio between the generation from RES and the total demand for a given region. Particularly, theoretical sustainability, can tolerate producing at full capacity, which implies an unitary utopian FC, just holding a comparative analysis.

For real sustainability, it is considered the effectively verified electricity production of electricity from RES. Indeed, the used methodology intended to reduce difference between the
calculated values for both described indicators in a global context, given a greater use for the regional potential, associated to each renewable source.

In 2012 Portugal checks a table of actual and theoretical sustainability of about 43.0% and 210.2%, respectively, obtaining a weighted CF of about 20.5% with respect to the generation technologies IC.

4 Model

4.1 MARKAL-TIMES

Developed in the late 90s by ETSAP (Energy Technology Systems Analysis Program) of the International Energy Agency (IEA), TIMES (acronym for: The Integrated Markal-EFOM System) is a generator of economic models for integrated energy systems, national or multi-regional, offering a rich technology base, and whose aim is to estimate the dynamics of long-term energy in multiple periods [21]. It is usually applied to the analysis of the entire energy sector, may, however, be applied only to a single sector, such as the sector under study (electricity sector).

The estimated final demand for the energy services is provided to the model, for each of the regions considered, along with the characteristics of the available technologies and future potential for primary energy sources. Using these inputs, TIMES aims to provide energy services meeting the minimum overall cost, minimizing the excess losses, and simultaneously making investments in terms of new equipment (technologies for electricity production in the case of the electricity sector) acting in the supply of primary energy and making market decisions by region [23]. The choice for generation technologies to be implemented in the future should be based on an economic and environmental criteria, if limits on GHG emissions are imposed.

4.2 Assumptions and Scenarios

This section presents the adopted considerations, related to some of the data, inherent to the used model, given the timeframe of the case study. In particular, it is necessary to resort to other studies, where it is indicated, specifically, the evolutions for: investment costs for new technologies to implement, fuel prices and future limits on GHG emissions and IC.

4.2.1 New technologies

The slope of the energy panning in production as it is studied, and given the natural increasing tendency for the future demand, making essential to implement new generation technologies. Thus aim to increase production levels, in particular, the increasing production from renewable basis, taking into account the environmental perspective, which seeks to achieve a successive reduction on GHG emissions over all the horizon time in the study.

Table 1 presents a listing of new technologies considered, where the evolution of investment costs and, in the case of thermal power plants, their efficiency is include. Were a linear variation for the presented values for 5 years samples is take into account.

Table 1 - Characteristics of the new technologies considered Technology Lifecycle to Generation Investment \([\text{€}2010/kWe]\) Efficiency [%] [14-8]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Life</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2010</th>
<th>2030</th>
<th>2050</th>
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<tbody>
<tr>
<td>Non-Renewables b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP</td>
<td>40</td>
<td>1571</td>
<td>1434</td>
<td>1298</td>
<td>1230</td>
<td>1163</td>
<td>42.9</td>
<td>52.0</td>
<td>54.9</td>
</tr>
<tr>
<td>IGCC</td>
<td>40</td>
<td>1780</td>
<td>1626</td>
<td>1471</td>
<td>1394</td>
<td>1318</td>
<td>46.9</td>
<td>53.0</td>
<td>59.9</td>
</tr>
<tr>
<td>NGCC</td>
<td>30</td>
<td>616</td>
<td>595</td>
<td>546</td>
<td>530</td>
<td>513</td>
<td>60.9</td>
<td>64.1</td>
<td>70.0</td>
</tr>
<tr>
<td>Renewables</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>25</td>
<td>1400</td>
<td>1270</td>
<td>1190</td>
<td>1150</td>
<td>1110</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offshore Wind</td>
<td>25</td>
<td>3000</td>
<td>2600</td>
<td>2380</td>
<td>2164</td>
<td>1950</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waves</td>
<td>25</td>
<td>5650</td>
<td>4070</td>
<td>3350</td>
<td>2774</td>
<td>2200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar PV</td>
<td>25</td>
<td>3378</td>
<td>1065</td>
<td>850</td>
<td>762</td>
<td>675</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSP/PTC</td>
<td>25</td>
<td>3574</td>
<td>3360</td>
<td>2904</td>
<td>2569</td>
<td>2200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSP/Tower</td>
<td>25</td>
<td>6993</td>
<td>6731</td>
<td>5051</td>
<td>3494</td>
<td>2200</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hydro technology is not considered, since it is not reasonable to proceed with a new installation only on the basis of the existing potential. It is now feasible to create a permitting process for the construction of a hydroelectric project that has not had a detailed evaluation study of potential environmental impacts, either up or downstream from its location [28].

4.2.2 Fossil fuel prices and GHG emission limits

These data corresponding to fuel prices are extremely important in the analysis, being an integral factor, given the investment decision related to the productions cost associated to the fossil fuel prices. For these it is assumed evolution values present in [8].

Environmental restrictions consider that, the electric sector should achieve a reduction in GHG emissions between 93 and 99% by 2050 compared with 1990 levels [7]. Accordingly, this sector should take a leading role in decarbonising the energy sector.

So, [9-10] was taken as reference [9-10], in which considers the evolution of these emissions for both Portugal and Spain.

4.2.3 Capacity limits

Table 2 shows the values for the development of capacity to be installed in Portugal and Spain:
Table 2 – Technical IC limits [1]

<table>
<thead>
<tr>
<th>Source/Technology [MW]</th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PORTUGAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>6800</td>
<td>7000</td>
<td>7500</td>
</tr>
<tr>
<td>Offshore Wind</td>
<td>75</td>
<td>4000</td>
<td>10000</td>
</tr>
<tr>
<td>Waves</td>
<td>5000</td>
<td>5000</td>
<td>7700</td>
</tr>
<tr>
<td>Solar</td>
<td>1500</td>
<td>9300</td>
<td>9300</td>
</tr>
<tr>
<td><strong>PORTUGAL:</strong></td>
<td>13375</td>
<td>25300</td>
<td>34500</td>
</tr>
<tr>
<td><strong>SPAIN</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>22000</td>
<td>30500</td>
<td>38000</td>
</tr>
<tr>
<td>Offshore Wind</td>
<td>375</td>
<td>20000</td>
<td>20000</td>
</tr>
<tr>
<td>Waves</td>
<td>25000</td>
<td>25000</td>
<td>25400</td>
</tr>
<tr>
<td>Solar</td>
<td>15000</td>
<td>49300</td>
<td>49300</td>
</tr>
<tr>
<td><strong>SPAIN:</strong></td>
<td>62375</td>
<td>124800</td>
<td>132700</td>
</tr>
<tr>
<td><strong>Iberian TOTAL:</strong></td>
<td>75750</td>
<td>150100</td>
<td>167200</td>
</tr>
</tbody>
</table>

Particularly for Portugal, future IC in each region was based on the following calculation:

\[ IC_f = IC_c + (IC_M - IC_c) \times F \]  

(2)

Where:

- \(IC_c\) is the current IC at the region;
- \(IC_M\) corresponds to the maximum capacity in Portugal for a given source/technology;
- \(F\) is the given region area/coast line length fraction, with respect to the total land area of mainland Portugal.

The coast line length refers to offshore wind and waves technologies.

The assignment of a capacity limit for each of the districts allows to safeguard an eventual installation of all capacity in just one or a few regions, in which the existing potential proves to be higher, which would not be realistic, given the natural limitations that each geographical region has.

[3] also refers to these limits, considering the potential of indigenous resources for electricity production, present in Portugal.

4.2.4 Adopted scenarios

Table 3 shows the nomenclature and characteristics considered for the eight scenarios analyzed:

<table>
<thead>
<tr>
<th>Electric system analysis</th>
<th>No</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portugal – Spain</td>
<td>C1</td>
<td>C3</td>
</tr>
<tr>
<td>Portugal (Disaggregated) – Spain</td>
<td>C2</td>
<td>C4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portugal – Isolated System</td>
</tr>
<tr>
<td>Portugal (Disaggregated) – Isolated System</td>
</tr>
</tbody>
</table>

Comparison between the scenarios C2 and C4 with and without limits on GHG (accounted for in CO\(_2\)e), essentially allows to verify the differences between the value of renewable and non-renewable existing IC, in regional terms, under the disaggregation method for both scenarios. On the other hand, confrontation between C1-C2 and C3-C4 allows to detect possible differences, given the existence, or not, of a disaggregation methodology.

Through the scenarios C5 to C8, the Portuguese electricity system is considered as an isolated system in order to compare the CO\(_2\) mitigation costs arising from C5-C6 and C7-C8.

4.2 Methodology Applied to the Model

Figure 11 presents schematically the application of the methodology to the created model.

The model was based on the Portugal-Spain model used in the study [1] to which a spatial disaggregation methodology was
applied and also considered consumption by activity sector and corresponding profiles consumption due to dynamic demand. It is still considered the real data for demand since 2005, the calculated demand trends by 2050, as the IC and CF for each region and technology.

5 Results and Analysis

Given to the computational limitations, the results for the presented evolutions by 2050, respect to a 5 years samples.

5.1 Regional Electricity Exchanges and Sustainability

Figure 12 present the average annual electricity exchanges from 2015 to 2050 for both scenarios C2 and C4.

The analysis reveals that the choice of each scenario appears to have a significant impact on this parameter, for which C2 is a reduction of both import and export. However, this can be explained by the high existing non-renewable C2 IC. Since there is no regional potential associated to power plants. Thus, the choice of regions to implement these centrals only should focus on the reduction of import/export, in regions with lower sustainability levels, given the losses associated to electricity transmission.

5.2 MIBEL Electricity Exchanges

The MIBEL import/export values for scenarios C1 to C4 reveals that the presence of a larger deployment in renewables (C3 and C4) appears to have a significant impact on export in a medium term, indicating an increasing on export balance from 2030 to 2050 (as shown in Figure 14).

In particular, when compared C3 and C4 scenarios, there is a slightly higher export balance than for the disaggregation method (C4). This can be determined by the renewable based technologies implementation in areas where the existing renewable potential presents greater than the average one which occurs in Spain, resulting on an export trend.

As for C1 and C2, and in line with the performed analysis to Figure 12, in which are the two scenarios that are not imposed any restrictions on GHG emissions (C1 and C2), the installation of power plants should only be based on a criterion of sustainability minor sustainability criterion, where, over the period and with an increase of this capacity, the export balance tends to be rather low. Nevertheless, its visible a difference between these scenarios on 2015-2030 period, which should relate to the already mentioned criteria for C3 and C4, alongside to a larger fraction of renewable electricity present in total production mix.

5.3 CO\textsubscript{2}e Emissions

Figure 15 shows the GHG emissions in CO\textsubscript{2}e for each of the scenarios (C1 to C4), where the reference value, assumed for electricity system in 1990 was about 16.7 million tons of CO\textsubscript{2}e.

C1 and C2 show an increasing trend across all the temporal horizon line at a higher fee than the one imposed for the reduction rate. Thus, in the absence of policy measures that

-8000 -6000 -4000 -2000 0 2000 4000 [GWh/Yr]

-25000 -20000 -15000 -10000 -5000 0 5000 10000 15000 20000 25000 C2 C4 Balance (C4-C2)

2005 2010 2015 2020 2025 2030 2035 2040 2045 2050

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Figure 14 - Evolution of Portuguese export balance in MIBEL (C1 to C4)

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C1 and C2 show an increasing trend across all the temporal horizon line at a higher fee than the one imposed for the reduction rate. Thus, in the absence of policy measures that
restricts this emission limits, it appears that this amount is about 2.5 times greater than that recorded in 1990 for the energy sector. More specifically, C2 shows a higher level of emissions after 2030 when compared to C1, which should be related to the import/export values, associated to the MIBEL (Figure 14) and subsequently to 2030. These balances tend to equate, checking for a lower emission level C2, given the increased presence of electricity from renewable sources in the energy mix for the C2 scenario.

Regarding to C3 and C4, there is a trend in line with the restrictions, and the slight discrepancy observed for the period between 2015 and 2030, in which C4 has slightly lower values, given the considered disaggregation.

5.4 Installed Capacity and Generation (C4)

Note that, the aforementioned Portugal and Spain IC technical limits are achieved by 2050 and, for all considered renewable technologies. These limits are directly related to the CO2 emissions restriction on emissions across all the time horizon, and that, by 2050, this values represent 4% when compared to the year 1990 levels, which lead to a great reduction of the thermal IC and hence to an even greater increase in renewable IC.

Given this, we immediately associate this saturation with a saturation in electricity generation, in which, and considering the Iberian system, total production did not show sufficient to attend all the demand. However, and contrary to the oceans and wind sources, solar power has three distinct technologies considered in this study, which correlate directly with different quantities of production, given the existence of a same potential. More precisely, when it reaches the solar capacity limit, the system must choose to implement technologies that despite representing higher costs, maximize the produced portion, which effectively holds for the year 2050 (Figure 16 (a)), where we can see a replacement for the solar PV by concentrated solar technology.

Figure 17 now shows the evolution of IC in 2050 for renewable based technologies considered in the study, due to the changes in demand.

For the Portugal-Spain system, it is visible a sufficient amount of production over demand in both cases C3 and C4 and an increase in output, with reference total demand over time, which could be related to a fraction increase in generation from renewable sources.

In order to study the effect of demand in the implementation of new technologies in 2050, and most of the scenarios referred to in 5.3 - Scenarios Adopted, it was used another scenario (C9), in which, proceeding, iteratively, to a change in demand values, with reference to the one present in scenario C6 (100%), where 0% respects to the 2012 real demand.

It should be noted that, the choice of implementing the onshore wind and PV technologies, when the given existing demand, production is not limited by the saturation capacity. Thereafter, system invests in offshore wind and waves, respectively, where, throughout this development, the implementing of each technology appears to relate only with some other capacity saturation.

This analysis reinforces the idea of a complementarity between solar FV and concentrated technologies, given the existing degree of freedom in this study for solar power, in which it is possible for the system to disregards the economic component in order to match supply, based on an imposed demand growing (Figure 18). Thus, the implementation of certain technology is not always associated with the lowest cost but with a need to ensure the supply component. It appears though, that a demand evolution of about 160% higher than C6, leads to a shortage in production, and where, all the installed solar capacity is represented by concentrated. This explains the
high export to Spain, when considered a 100% demand evolution (see Figure 14).

Thus, it appears that the technical limitations inherent in the installation of new capacity may, significantly affect, costs associated with the need to implement technologies in a medium and long-term, that are not as profitable in economic terms, in order to ensure the correct energy supply.

### 5.5 Mitigation Costs

Once are not assumed import/export prices, related to MIBEL, for purposes of calculating the costs associated to the GHG mitigation are used the C5 to C8 scenarios in which, Portuguese electricity system is considered as an isolated system.

These costs are based on:
- Cost_Act: activity costs that directly relate to energy production;
- Cost_Fom: fixed maintenance costs;
- Cost_Flo: Cost of fuel imports;
- Cost_Inv: Investment costs.

Figure 19 shows the development of mitigation costs, associated with mentioned pairs of scenarios.

We can see that scenarios without breakdown (C5-C6) displays a lower mitigation costs from 2030 to 2035, and that after this time, shows higher costs when compared to the disaggregated model scenarios C7-C8. This fact should relate to an investment in thermal power plants in the absence of a disaggregation (C6), representing a lower total cost, while, in C8, the system chooses to introduce renewable technologies, as some regions experiencing higher potentials, leading to compensation in the medium term. After this and in line with the reductions in emissions, there is a "requirement" for deploying core based on RES and the C5-C6 costs prove to be higher.

The steady increase of these costs, for both analyzes, should also relate to the aforementioned IC saturation CI, leading to invest in technologies that represent higher levels of production given the same capacity, which, nevertheless, represent over high costs.

### 6 Conclusions and Future Work

An increase in the deployment of renewable, Portugal allows an exporter to obtain medium-term balance, and to include analysis where the methodology of disaggregation, there is a slightly higher balance, given the choice to install initially, central in regions that verify a greater CF.

Technical limits to the CI directly influence the installation of new power plants, where it appears that a particular technology is implemented as a function of saturation in some other CI. This has a direct effect on the costs of electricity sector, leading the system to choose the deployment of more efficient technologies in order to increase productivity at constant capacity, given the need to supply, which contributed to the steady rise in costs mitigation over time.

Also, a disaggregation scenario allows a significant reduction of the rising costs of mitigation, associated with limits on greenhouse gas emissions, compared to the scenario in the absence of this methodology. Also an extinction dependence on import and export dominance, when considering the Portuguese electricity system integrated into the Luso-Spanish system.

For more detailed future work to estimate trends in demand, given the regions considered studies could be included.

The differentiation of the regional production curves for the waves technology as well as the methodology applied to Spain, while contemplating the integration of the electrical system of Portuguese with Spanish, would strengthen the application of the same, which is to be expected that the differences between scenarios (with and without disaggregation) are more notorious and/or conclusive.

Should still be considered the real impact on the economic component of the IC limits, studying in more detail these values for the given regions where a methodology of spatial disaggregation is considered. Just as the introduction of a wider range of new generation technologies to be implemented in order to reduce the limitations imposed by a possible capacity saturation.

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**References**


[20] Krajačić G., et. al., 2011. How to acheive a 100% RES electricity supply for Portugal?


