Effects of Climate Change on Power Supply: Long-term Analysis for the Portuguese Study Case

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Abstract — **This Thesis, developed in collaboration with project Clim2Power, assessed the effects of climate change on future Portuguese electricity system, considering regional allocation of renewable electricity sources and the different impact of climate change across the country. For this purpose, results from 11 regional climate models were applied to a dispatch optimization model. The study also evaluated the adequacy of power system from the national energy plans for years 2030 and 2050, Plano Nacional Energia e Clima 2021-2030 (PNEC) and Roteiro para Neutralidade Carbonica 2050 (RNC2050) respectively, under climate change. These were used as guidelines to model the electricity system, applying the planned capacity mix, and comparing results with the goals set. For both years, two climate variability scenarios (RCP 4.5 and RCP 8.5) and a constant historic climate scenario were considered.**

The electricity system resulted being impacted by a combination of climate variability and dispatch events, such as curtailment and lost load. An overall drier future climate was observed for 2030 and 2050. Specifically, a major impact on hydropower in the Non-Douro basin was registered, more consistently affected by reduced availability than Douro basin in both years. No significant variations at regional level were obtained for PV and wind compared to constant climate scenario.

Results for 2030 showed an overall compliance to PNEC goals, with only electricity-related CO2 emissions overshooting the emission limit. Regarding 2050, outcomes revealed difficulties to reproduce RNC2050 scenario, yielding large amount of lost load and consequent exaggerated costs of supply, particularly under climate change.

Keywords — **Climate Change, Energy Modelling, Renewable Energy, Dispatch Optimization, Portugal**

I. INTRODUCTION

The energy sector is undergoing an extraordinary moment in its history, mirror of societal changes and of the quickly evolving background. Ever since Paris Agreement in 2015, an awaken consciousness favoured by risen mediatic attention on the effects of climate change has finally put focus on the urgency of energy transition to more environmentally and sustainable practices. With the goal of keeping global temperature increase below the 1.5°C to prevent catastrophic climate change [1], Governments are defining targets, promoting and applying incentive measures, while the first tangible effects of climate change are starting to reveal.

In 2016, one year after Paris Agreement, Portugal has defined the political target of becoming a carbon neutral country within 2050. This implies a reduction of the national greenhouse gas (GHG) emissions between 85% and 90% by 2050 compared to 2005, as set by the Carbon Neutrality Roadmap 2050 (RNC2050) [2]. The emission reduction trajectory was set between 45% and 55% by 2030, highlighted in the National Energy-Climate Action Plan (PNEC2030), which defined targets, policies and measures and represents the main national climate and energy policy tool for 2021-2030 period [3]. Although all sectors of economy must reduce GHG emissions, the energy sector will contribute the most, playing an especially relevant role in energy transition towards a decarbonised society. To achieve such goal Portugal aims to reinforce the weighting of renewable energy on final energy consumption, setting the goal of 47% of RES consumption in 2030, associated with 80% of renewable electricity which should grow to almost 100% by 2050. At the same time, the country is located on an acknowledged hotspot of climate change. Projections show a considerable change towards higher average temperatures, lower precipitation rates and more frequent and severe droughts, with increased asymmetry in seasonal and spatial distribution [4], [5], [6], which may affect Portugal power system. From this, the motivation for conducting the present study: modelling the future electricity system while accounting for climate change effects on the performances of VRES at a high spatial resolution, using Portugal as a case study.

This thesis has a twofold objective:

- Assess the effects of climate change on power supply in Portugal Mainland, considering the allocation of the VRES on the territory, the regional asymmetry of climate variability, and investigating the different output between national regions;
- Evaluate the adequacy of power supply scenario defined in PNEC and RNC2050 for the years 2030 and 2050, respectively under the effect of climate change.

To do so, a regional disaggregated dispatch optimization model for the Portuguese power system was built under this thesis using Dispa-SET model generator [7]. Two climate scenarios, simulated through eleven regional climate models (RCMs) and the impact of their climate variables outputs on VRES technologies (modelled within the project Clim2Power framework), were used as performance indicators of VRES in Portugal and applied to the Dispa-SET-PT. The model solves the unit commitment problem, simulating so the optimal operation of the electricity system during a desired timeframe.

II. LITERATURE REVIEW

An easy way to comply with the conference paper formatting requirements is to use this document as a template and simply type your text into it.

A. *Similar Studies*

Climate change and its effects on energy systems have been widely addressed by research in the past years. Extreme weather events induced by global warming are experiencing a significant intensification, producing severe damage, and introducing new challenges as they become more usual. Related to this, the need of limiting the irreversible disruptions that the overshooting of 1.5°C increase would cause. The ongoing transition to more electricity-based consumption reserves several challenges along the way: the extremely variable nature of renewable energy systems and their dependency on weather, make them profoundly affectable by climate change. Investments considered profitable today might not take future climate into account. Both demand and supply could largely be distorted in the long-term and it is important to consider climate change scenarios, worst cases especially. Similarly to this study, [8] and [9] make use of regional climate models to assess variations in the European electricity system under different climate change scenarios. Results present moderate shifts in power production, mainly due to the compensation of the effects on the demand. However, these kind of studies do not provide specific insights for a restricted region. In general, what was observed from the literature analyzed is that the more region-focused is a study, the more technology specific it gets, enhancing the reliability of the outcomes. Furthermore, only accounting for a technology or making use of wide clusters could lead to misinterpretation of the results, as other technologies could be affected by the same causes in a completely different way and with different intensity locally.

B. *Models and Tools for Energy Systems*

Several comparison papers, guides and reviews were analyzed to identify the most renowned and used models and tools, distinguishing by main application, enhanced features, availability, and fitness to the case study. The most required features to be provided by the tool were listed and ranked. As PNEC2030 and RNC2050 were modelled using capacity expansion models optimizing the investment costs, the counter proof needed for validation is a dispatch optimization model, optimizing the operation of the electricity system. [10], [11], and [12] were used as catalogues of modelling tools, to generate a shortlist of mainly open source models to further investigate on. Next, a review of the most significative study cases applying those models was made, eventually identifying a smaller selection of suitable choices. The most promising tools selected were SWITCH, Balmorel, Dispa-SET, TEMOA, and OSeMOSYS. Overall, anyone of those would represent a good choice, but mainly for its Europe-oriented formulation, high customizability and for its ongoing application within Clim2Power framework, Dispa-SET was chosen among the others.

III. METHODOLOGY

The main input data used in the analysis was generated within the Clim2Power project framework. Capacity mixes for 2030 and 2050 were retrieved from the respective National Plans, as well as the goals used for comparison with the results. Fig. 1 summarizes the main points of the methodology applied to the study.

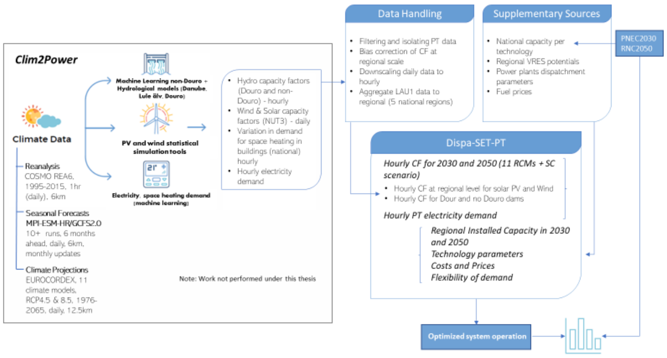

Fig. 1. Methodology flow-chart

C. *Clim2Power project*

Clim2Power project aims to translate results derived from complex scientific models into useful decisional tools for end-users. The expected outcome of the project would be a web-based climate service assessing the effects of future climate on variable and weather-dependent energy technologies, namely PV, wind, and hydropower. Clim2Power addresses also heating and power system and demand evolution in relation to climate conditions as support tools for both private and public customers [13]. Pilot sites of the project are Portugal, Germany and Austria, Sweden, and France, however the focus is Europe wide oriented. For the case of Portugal, solar PV and onshore wind CF were projected at municipality level, following the standardized Local Administrative Units (LAU 1) aggregation level. Climate-related projections on Douro basin were also modelled within the project framework.

D. *Climate Scenario and Models*

The Fifth Assessment report (AR5) by IPCC defines 4 different pathways to the year 2100, accordingly to the effectiveness of the measures adopted in climate and energy policy to tackle climate change. In this study, only RCP 4.5 and 8.5 were considered.

RCP 4.5 forecasts a moderated intensity of climate change, while RCP 8.5, projects more disruptive effects. Under such scenarios, projections in terms of variable renewable energy systems performances and electricity demand were provided by Clim2Power for 11 regional climate models. A third scenario simulating the absence of climate change, namely climate constant (CC), was considered to make comparisons with a neutral situation. For CC scenario, historical capacity factor of PV, wind, and hydropower were used instead of projections, as well as demand which was retrieved from real observations and upscaled to match the future increased electricity need.

E. Data handling

For this study, Clim2Power project allowed sharing the electricity demand and capacity factors of PV, onshore wind and hydroelectric for both RCP 4.5 and 8.5, as well as for each one of the eleven climate models implemented. Each of the 273 local administrative units (LAU 1) corresponds to a projected capacity factor for PV wind turbines and hydroelectric power plants for every day of the year at mid-day, in the time frame from 2016 to 2065. Furthermore, national hourly demand was provided for 2030 and 2050. Pandas, Python data analysis library, was implemented on the sets of data provided by Clim2Power to shape their formatting features as required for compatibility with Dispa-SET and eliminate useless information.

For a better representation of the variability of renewable energy sources, daily capacity factors were transformed to hourly, at best respecting the daily characteristic patterns of each source when discernible. A bias correction to the projected capacity factor of wind and PV was also applied, as regional climate models present limitations at high granularity resolutions in terms of scale between model and reality. To tackle this cause of uncertainties, bias correction can be calculated to reduce the gap between simulation and historical observation.

$$CF'_{fut} = CF_{fut} \times \left(\frac{\overline{CF}_{obs,hist}}{\overline{CF}_{sim,hist}}\right) \qquad 1$$

Where CF'_{fut} is the bias corrected projection of future capacity factor at noon, CF_{fut} is the unbiased future capacity factor resulting from simulation, $\overline{CF}_{obs,hist}$ is the median of historical observation of capacity factor at noon, and $\overline{CF}_{sim,hist}$ is the median of capacity factor at noon resulting from the simulation of historical capacity factor. Due to the lack of location-specific historical observations, to apply the bias correction with the change factor method, a reference location for PV and wind had to be selected

$$CF'_{fut,l} = \frac{CF_{fut,l}}{CF^*_{fut}}\left(CF^*_{fut} \times \left(\frac{\overline{CF}_{obs,hist}}{\overline{CF}_{sim,hist}}\right)\right) \qquad 2$$

Being $l = \{1, \dots, 273\}$ the list of considered Portuguese municipalities and CF^*_{fut} the projected capacity factor of the reference municipality at noon. No bias correction was applied to hydropower availability factor, as the data was provided already bias corrected.

F. Dispatch Optimization Model

Dispa-SET is an open-source unit-commitment problem solver and dispatch model developed by JRC, with the main scope of modelling European energy system. It allows for high customizable features and formulations depending on data availability, desired accuracy, and focus.

It is completely written in Python, making use of libraries such as Pandas, Numpy, Matplotlib and others. Once generated the optimization problem, it is solved in GAMS environment, which Dispa-SET communicates with through a GAMS application programming interface [14]. The optimization can run in linear programming (LP) and mixed-integer linear programming (MILP) formulation. LP formulation requires significatively less computational power, however clustering of similar generation units (power plants) occurs. To maintain the desired degree of granularity, MILP formulation was applied in this study. In this case binary variables are used to indicate the status of commitment of a generating unit. The goal of the optimization is to minimize the operational costs of the systems, namely the cost of supply. A look-ahead optimization approach is used to roll the horizon throughout the timeframe of the simulation. For this study, a weekly (7 days) optimization horizon was chosen. Path to input datasets, parameters and simulation options are user-defined in a configuration file in ".xlsx" format. Equation 3 report the objective function minimized by the model.

$$\begin{gathered}\min \Big[\textstyle\sum_{u,i} CostFixed_u \cdot Committed_u \cdot TimeStep + \\ \textstyle\sum_{u,i}\left(CostStartUpH_{u,i} + CostShutDownH_{u,i}\right) + \\ \textstyle\sum_{u,i}\left(CostRampUpH_{u,i} + CostRampDownH_{u,i}\right) + \\ \textstyle\sum_{u,i} CostVariable_{u,i} \cdot Power_{u,i} \cdot TimeStep + \sum_{i,n} VOLL \cdot \\ \left(LL_{MaxPower,i,n} + LL_{MinPower,i,n}\right) \cdot TimeStep + \textstyle\sum_{i,n} VOLL \cdot \\ \left(LL_{2D,i,n} + LL_{2U,i,n} + LL_{3U,i,n}\right) \cdot TimeStep + \textstyle\sum_{u,i} VOLL \cdot \\ \left(LL_{RampUp,u,i} + LL_{RampDown,u,i}\right) \cdot TimeStep\Big]\end{gathered} \qquad 3$$

$CostFixed_u$ being the fixed costs related to unit u operation, while $Committed_u$ indicates whether the same unit must run or not during the duration of the $TimeStep$ of optimization. $CostStartUpH_{u,i}$ and $CostShutDownH_{u,i}$ are the costs of starting-up and shutting-down unit u at the timestep i, respectively, as $CostRampUpH_{u,i}$ and $CostRampDownH_{u,i}$ are the costs related to increasing and decreasing power production, respectively. $VOLL$ is the value of lost load and is multiplied by lost load components, namely:

- $LL_{MaxPower}$: deficit in maximum power
- LL_{2D}: deficit in reserve-down
- LL_{2U}: deficit in reserve-up
- $LL_{3U,i,n}$: deficit in reserve-up, non-spinning

G. Input data

The installed capacity to be applied to years 2030 and 2050 was retrieved from PNEC2030 and RNC2050, respectively. New capacity installed, revamped, or dismissed for every technology was appraised and the new capacity mixes were obtained. The installed capacity for power generation divided by fuel is presented in Table I.

TABLE I

FUTURE INSTALLED CAPACITY

Installed capacity [GW]	PNEC2030	RNC2050
Coal	0.0	0.0
Natural gas	2.8	0.0

Fuel Oil	0.0	0.0
Hydroelectric	5.1	5.1
Pumped hydroelectric	3.4	3.4
Onshore wind	9.0	12.0
Offshore wind	0.3	0.243
Solar PV	9.0	26.36
Biomass	0.5	0.088
Batteries	0.0	4.132

1) *Thermal power plants:* Furthermore, PNEC2030 does not consider cogeneration (CHP), so also the natural gas (NG) and biomass values reported for 2050 in Table II are only representative of conventional thermal generation. For all dispatchable power plants, unit commitment values must be defined. Table II reports values retrieved from [15] and [16] for the only two thermal power plants types present in the modelling, namely combined cycle gas turbine (CCGT) and biomass fuelled steam turbine (STUR).

TABLE II

UNIT COMMITMENT PARAMETERS

Unit commitment value	CCGT	STUR
Efficiency [%]	57.0	46.0
Efficiency at minimum load [%]	51.0	35.0
Minimum load [%P_{nom}]	45.0	35.0
Ramp up rate [%]	4.0	2.0
Ramp down rate [%]	4.0	2.0
Start-up time [h]	4.0	1.0
Minimum up time [h]	4.0	4.0
Minimum down time [h]	2.0	6.0
No-load cost [€$_{2020}$/MW]	0.0	10.6
Start-up cost [€$_{2020}$/MW]	47.0	102.4
Ramping cost [€$_{2020}$/MW]	0.0	1.3

2) *Renewable power plants:* To account for a reliable regional allocation of each source, [10] was used as supplementary of PNEC2030 and RNC2050. The PV and wind potential at net of land use constraints is shown in Fig. 2 and Fig. 3, respectively.

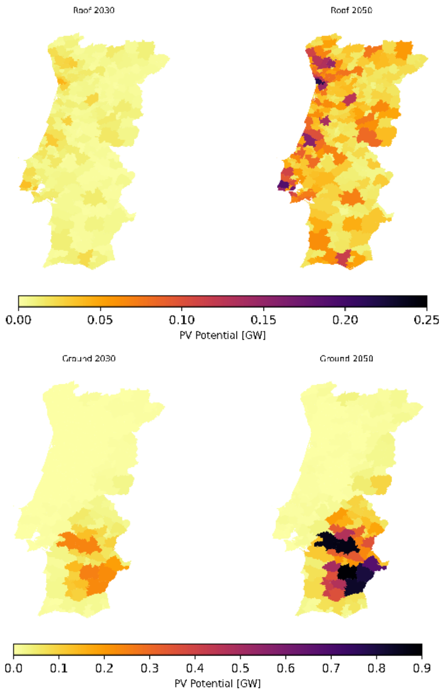

Fig. 2. Capacity potential for PV (residential = roof)

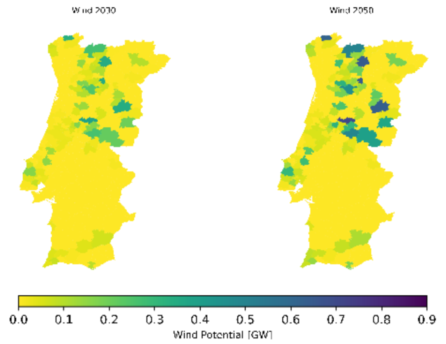

Fig. 3. Capacity potential for wind

3) The share of each municipality was then clustered into regions and the capacity set by PNEC2030 and RNC2050 was applied, resulting in the allocated capacity reported in Table III and

4)

5)

6)

Table IV for PV and wind, respectively.

TABLE III

REGIONAL ALLOCATION OF PV CAPACITY

[GW]	Alentejo	Algarve	Centro	Lisboa	Norte
2030	4.86	0.39	1.06	1.55	1.13
2050	14.07	1.23	4.59	2.34	4.12

TABLE IV

REGIONAL ALLOCATION OF WIND CAPACITY

[GW]	Alentejo	Algarve	Centro	Lisboa	Norte
2030	0.18	0.39	5.14	0.93	2.35
2050	0.24	0.52	6.86	1.24	3.38

Regarding hydropower fleet, due to the minimal differences in capacity between year 2030 and 2050, made uncertain by the range provided in PNEC2030, hydroelectric stations were assumed to stay constant in both years. Since Clim2Power put focus on the Douro region, tailored data was made available for the power plants in the basin. For this reason, and for lack of information on stations in other basins, hydropower capacity was clustered into Douro and non-Douro, and subclustered as pumped and conventional.

TABLE V

HYDROPOWER FLEET BY CLUSTER AND TECHNOLOGY

Plant name	Basin	Type	Power capacity [MW]
Miranda	Douro	Conventional	369.0
Crestuma-Lever	Douro	Conventional	117.0
Baixo Sabor	Douro	Pumped	189.0
Bemposta	Douro	Conventional	431.0
Pocinho	Douro	Conventional	186.0
Valeira	Douro	Conventional	340.0
Regua	Douro	Conventional	180.0
Carrapatelo	Douro	Conventional	201.0
Foz Tua	Douro	Pumped	261.0
Vilar de Tabuaço	Douro	Conventional	58.0
Torrão	Douro	Pumped	140.0
Varosa	Douro	Conventional	25.0
Gouvães	Douro	Pumped	880.0
Daivoes	Douro	Conventional	114.0
Vidago	Douro	Conventional	160.0
No Douro Pumped	Other	Pumped	2330
No Douro Conventional	Other	Conventional	2410

7) *Batteries:* Battery storage represents a significant share in the capacity mix of 2050. Since no further information is provided in RNC2050, the fleet was assumed to be entirely comprised of lithium-ions stationary batteries for VRES ancillary service. As RNC2050 does not report about the storage capacity, nor the specifics of the battery model used to draw the capacity estimation, the maximum charging capacity was retrieved by [18]. As for energy shifting application batteries, the inbuilt cost estimation tool provided by IRENA suggests an energy-to-power ratio of around 8 kWh/kW. This factor yields 32 GWh of maximum storage capacity for an installed power capacity of 4.1 GW. No battery profile was imposed to the model so the charging and discharging of the reservoirs could be optimized during the simulation.

8) *Interconnections:* The Total Transfer Capacity (TTC) between Portugal and Spain is currently 3 GW. TYNDP 2016 [19] sets an increase of 15% in TTC for the Iberian Electricity Market (MIBEL) within 2030. However, due to the complex European electricity system, uncertain future investments, and evolution of the markets, it is hard to elaborate a reliable scenario. To properly model the interconnections and account for realistic energy flows, Spain (at least) would have to be modelled as well [20]. Thus, Portugal was modelled as a closed system.

9) *Electricity Demand and Flexibility:* Clim2Power project computed electricity demand evolution based on demand from RNC (adjusted for 2030), combined with the RCMs to apply the effects of climate change.

TABLE VI

MEAN DEMAND FOR RCP AND CC SCENARIOS

2030			2050		
RCP 4.5	RCP 8.5	CC	RCP 4.5	RCP 8.5	CC
59.50 ± 0.97	59.37 ± 0.97	59.15	71.45 ± 1.45	71.30 ± 1.45	71.32

With such high share of variable renewables, demand-response adoption becomes a must for providing extra flexibility and compensate for the lack of reliable, dispatchable units. For this reason, literature sources estimating potential demand flexibility in the future were considered. [21]was used to understand to what extent demand could be theoretically shifted in 2030 and flexible demand share was set to 3% of total load. Regarding 2050, defining a reliable portion of deferrable demand was harder task. [22] combined with [23] suggest the adoption of 9% of total demand.

10) *Costs and Prices:* Fuel prices and other user-defined costs can either be provided in hourly data for the whole timeframe of the simulation or set to a default value through the configuration file. Price forecasts for NG can be found in several pieces of literature, however for this study the projection made by [24] was applied. Not such availability of information was found for biomass, so the forecasts was calculated using historical hourly price of biomass for year 2016, applying the observed inflation rates until 2020. From 2020 to 2050, an inflation rate of 2% was used instead.

TABLE VII

FUEL PRICES FOR 2030 AND 2050

€/MWh	Natural Gas	Biomass
2030	23.2	46.43

2050	26.97	68.99

The estimated price of CO2 for years 2030 and 2050 depends on various factors. The EU-proposal for the price of CO2 retrieved in [25] was used as input to the model, setting the permit price at 50 €/ton of CO2 for 2030 and 2050. Eventually, a value of lost load (VOLL) had to be set mainly to calibrate the model and obtain simulated cost of supply in the same order of magnitude as the current costs. [26] suggests a value of 5120 €/kWh specifically for Portugal.

IV. RESULTS

Only main results from simulations are here reported. The focus of the analysis was put on the differences in generation, demand fulfilment, CO_2 emissions and cost of supply between the scenarios considered. Due to the large number of climate models used for each scenario, results are presented in terms of mean output, with error bars indicating the range between 90 and 10 percentiles.

H. *Year 2030*

The generation mix resulting from optimization and simulation of the three scenarios for 2030 is presented in Fig. 4. Most notable outcome is the drop in hydropower production for both RCP scenarios in comparison to SC scenario.

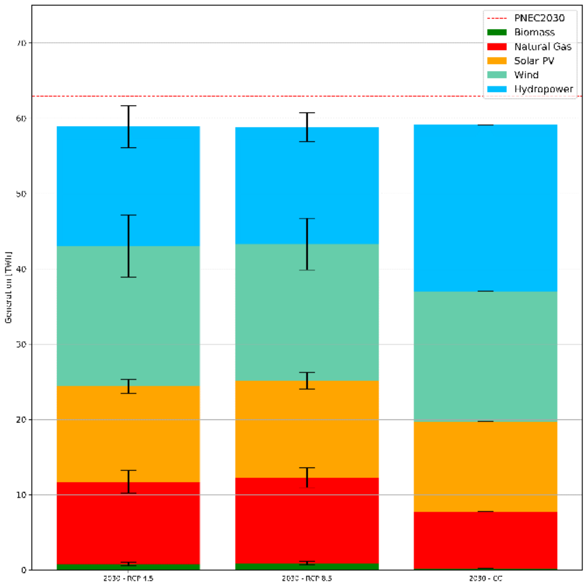

Fig. 4. 2030 generation mix for RCP and SC scenarios

To address the causes of differences in generation between scenarios, dispatch events such as curtailment of VRES had to be investigated. Curtailment can be responsible of reductions in CF of up to 60% in systems without storage, according to [26]. CC scenario presents more evenly distributed share of curtailment by VRES, while hydro is largely the most curtailed source in both RCPs, with more than 70% of the total. This can be related to the fact that larger amount of curtailment occurs between spring and summer in climate variability scenarios, when hydro presents higher availability and PV generation peaks thanks to longer periods of sunshine. Regarding CC scenario, curtailment peaks in March and remains quite constant during the rest of the year, explaining the more distributed curtailment between VRES.

Table VIIITable VIII reports the CF of PV, wind, and hydropower in 2030. Values are inclusive of the overall system operation effects. As expected, no big variation in PV and wind CF is observable between the two RCP scenarios. Considering the significantly high PV and wind curtailment occurring in CC scenario, RCPs present an increased CF for both the technologies. Thus, it is unlikely that this result might represent some sort of climate change effect. As for hydropower, the decrease in availability observable in RCP 4.5 becomes slightly larger in RCP 8.5. For the same reasons just mentioned, this result is to be read as combination of both climate change effects, and higher hydro curtailment in RCP scenarios in respect to CC.

TABLE VIII

2030 NATIONAL CAPACITY FACTOR RESULTING FROM MODELLING

	Historical	RCP 4.5	RCP 8.5	CC
Solar PV	18.5%	15.1%	16.3%	16.1%
Wind	24.6%	21.2%	22.3%	23%
Hydro	35%	29.7%	20.8%	21.2%

There is presence of lost load in both RCP scenarios, which accounts for less than 2% of total demand. Such small amount could be fully covered by the presence of interconnections with Spain [20]. CC scenario presents a negligible amount of lost load.

Regarding the compliance with the goals set by PNEC2030, renewable electricity (RES-E) share surpasses the 80% of total generation in all scenarios (mean of the RCMs for RCP scenarios). However, some RCMs would yield RES-E shares just below the goal. Furthermore, neither RCP 4.5 nor 8.5 succeed respecting the limit of CO_2 equivalent emissions, as shown in Fig. 5.

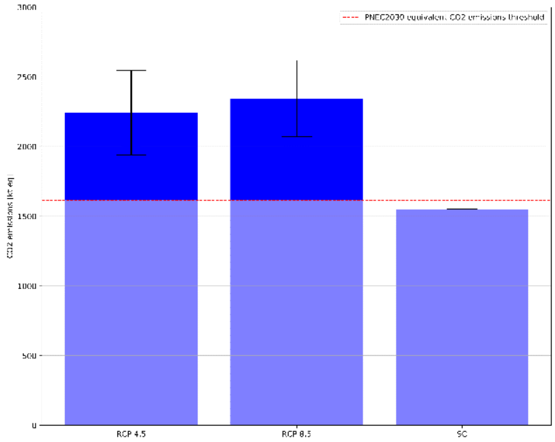

Fig. 5. 2030 cumulative CO_2 equivalent emissions for RCP and SC scenarios

Eventually, yearly average costs of supply (wholesale market values) for 2030 are reported in Table IX.

TABLE IX

AVERAGE COST OF SUPPLY [€/MWH]

RCP 4.5	RCP 8.5	SC
73.11	78.97	11.25

The order of magnitude of the costs presented above is in line with recent costs of supply, between 51 €/MWh and 53 €/MWh (2017) according to [28]. With 80% of RES-E, the system should be able to provide service at lower costs: [28] projects an optimized system operation cost of about 45 €/MWh for a high RES-share scenario in 2030. Higher costs can be related to presence of lost load due to the absence of cross border interconnections.

I. Year 2050

The generation mix resulting from the simulation of the three scenarios in 2050 is shown in Fig. 6. Once again, most notable outcome is represented by a minor generation from hydro in RCP scenarios, in respect to CC scenario. The total absence of NG power plants in the capacity mix leads to 100% of RES-E and almost null CO_2 equivalent emissions, largely under the limit of 168 kt set by RNC2050.

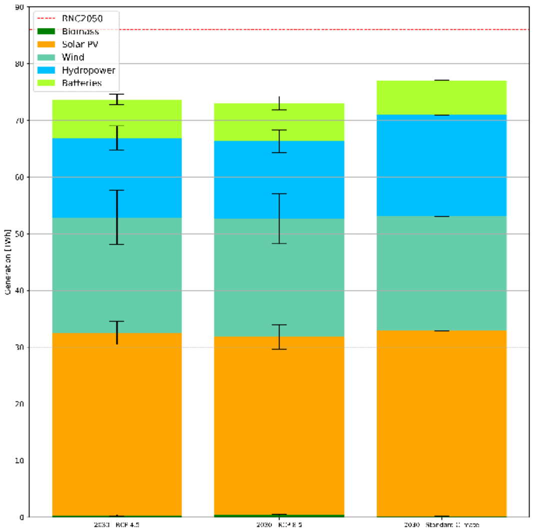

Fig. 6. 2050 generation mix for RCP and SC scenarios

Like in 2030, curtailment is high during spring and summer, and peaks in the early afternoon there's maximum PV generation. However, VRES are curtailed more equally in 2050, allowing to draw safer conclusions in terms of climate change induced effects. A summary of the resulting CF of the three technologies after the simulation is proposed in Table X

TABLE X

2030 NATIONAL CAPACITY FACTOR RESULTING FROM MODELLING

	Historical	RCP 4.5	RCP 8.5	CC
Solar PV	18.5%	14.1%	13.6%	14%
Wind	24.6%	18.8%	19.4%	19%
Hydro	35%	24%	18.4%	18.8%

In general, results project a drier climate in respect to CC scenario, reinforced by the fact that curtailed hydro is larger in comparison to RCP scenarios. Regarding PV, the slight decrease in RCP 8.5 in respect to the other scenarios is relatable to more curtailment share of PV.

Although the solid presence of energy storage to provide the system with increased flexibility, yet the total absence of conventional dispatchable units appears not to be fully compensated. A considerable amount of lost load occurs on almost every day of the simulated year, meaning the stationary battery capacity is not sufficient to overcome the variability of the generation. Fig. 7 shows the cumulative lost load for each scenario, divided by type of deficit. Consistently with curtailment, lost load is registered in winter and fall, when climate tends to be drier and days are shorter. Fig. 8 and Fig. 9 are dispatch plots of a winter week and summer week, respectively, of all scenarios. RCM "A" was randomly chosen for representation of climate variability scenarios. On a daily basis, lost load typically occurs at morning and early in the night due to the absence of PV generation and high electricity demand.

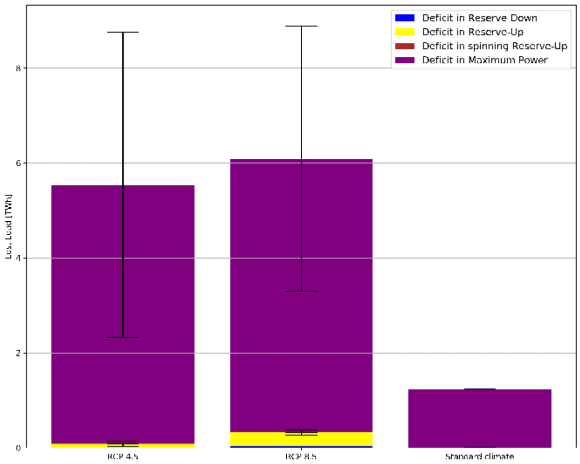

Fig. 7. 2050 cumulative lost load for RCP and SC scenarios

Lost load in both RCP scenarios reaches about 10% of total demand, meaning poor reliability of the electricity system. Unlike in 2030, there is a high uncertainty if such a high share could be fully compensated by the presence of realistic cross-border exchanges. Even so, it would determine a too high dependency on Spanish electricity system, to which Portugal is likely to become exporter rather than importer in the future according to [29] and [20]. CC only presents approximately 2% of total demand, which is more relatable to the absence of interconnections.

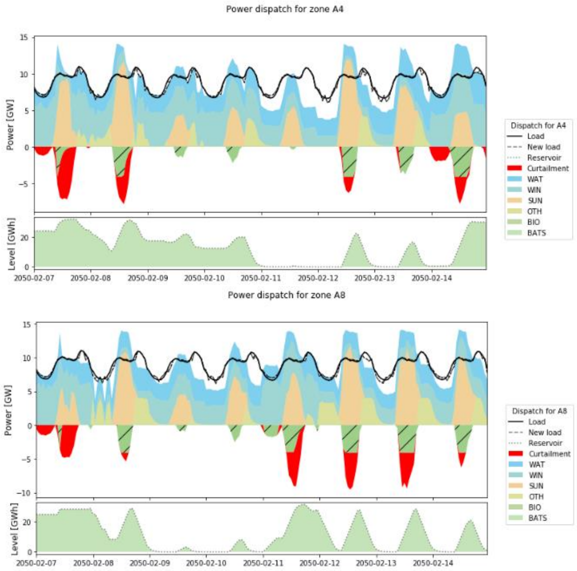

Fig. 8. 2050 cumulative lost load for RCP scenarios

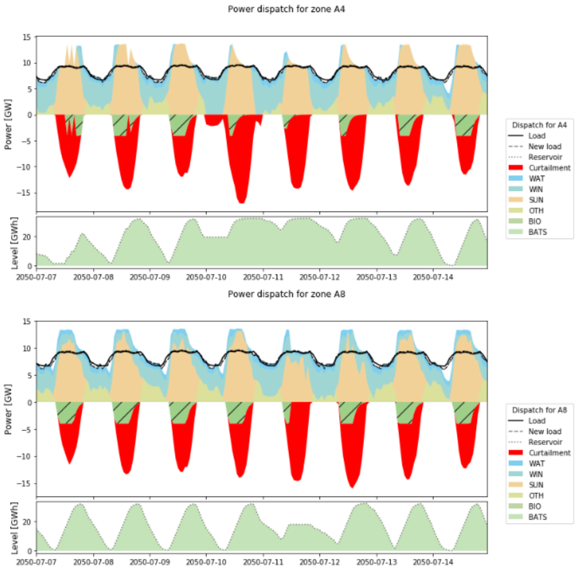

Fig. 9. 2050 cumulative lost load for RCP scenarios

The gap between generation and demand also affects the benefits provided by batteries, which are not able to store when surplus energy is not generated, increasing so the deficit in timeframes that would require the intervention of reserves (night-time). The yearly average depth of discharge (DOD) batteries experience during operation is 58, 57.7, and 52.4% for RCP 4.5, 8.5, and CC, respectively. In general, these results are quite low if compared to declared DODs for lithium-ion batteries of 80-100% and might indicate a wrong (underestimated) installed capacity for the system.

The unreliability of the system is translated in exaggerated costs of supply, reported in Table XI. Although CC scenario presents a fair average cost of electricity, it is about 7 times higher than its counterpart in 2030.

TABLE XI

AVERAGE COST OF SUPPLY [€/MWH]

RCP 4.5	RCP 8.5	CC
381.29	427.31	78.25

The unsatisfactory results deriving from the modelling of Portuguese electricity system in 2050 under RNC2050 capacity mix and climate variability led to the decision of conducting a sensitivity analysis, investigating possibly more adequate configurations of the system. Battery storage capacity and share of flexible demand were determined as parameters for the study. Assuming the scenarios presented above as the “low batteries - low flexibility” (LOB-LOF) option, other three sub-scenarios were considered:

- Low Batteries – Low Flexibility (LOB-LOF): 9% of flexible demand and 4.1 GW of installed batteries (base case from RNC2050)
- High Batteries – Low Flexibility (HIB-LOF): 6 GW of installed battery capacity, 9% of flexible demand
- Low Batteries – High Flexibility (LOB-HIF): 4.1 GW of battery storage and 13% of flexible demand
- High Batteries – High Flexibility (HIB-HIF): 6 GW of battery storage and 13% of flexible demand

Results were jointly compared in terms of VRES curtailment, lost load, and average cost of supply. The desired configuration would yield the least amount of lost load and curtailment at the minimum cost. The analysis suggests HIB-LOF sensitivity analysis scenario (“high” batteries and “low” demand flexibility) as the best one for all climate scenarios. With this configuration, the average cost of electricity for 2050 would decrease of approximately 36 and 37% for RCP 4.5 and 8.5, respectively when comparing with the base case scenarios. Despite this reduction 2050 presents high cost of electricity still (relative to recent past and 2030). This is due to the presence of lost load, even if reduced of 35 and 40% in RCP 4.5 and 8.5, respectively, compared to base cases. Such improvement would reduce lost load to around 5% of total demand in both RCPs.

V. CONCLUSIONS AND FUTURE WORK

Several efforts are being made by the Portuguese Government to decarbonize the electricity sector. However, due to the geo-location of Portuguese Mainland, the country is bound to be consistently affected by climate change, with likely negative effects on VRES. It is from such considerations that the main question this thesis aims to reply originated: *To what extent is climate change bound to affect Portuguese power system?*

A reduction in capacity factor (CF) from historical values for all renewable technologies and scenarios was detected. Hydro appeared to be the most affected by climate change, with large deviation from historical performances, represented by the average hydrologic year 2011. Year 2030 presented a wider gap in terms of hydro generation between climate variability scenarios and the constant climate (CC) scenario than 2050. However, this outcome must be read considering the high share of curtailed hydro in respect to PV and wind in 2030.

Will there be significant differences in the way climate change affects the electricity system regionally?

In general, no significant variations in terms of PV nor wind were registered regionally due to climate variability. In the case of hydro instead, clustered into Douro and Non-Douro basins, a higher sensibility to climate change effects resulted for Non-Douro cluster. However, the absence of regional historical data made comparison with climate variability subject to higher uncertainty, underlining the need to register and make available electricity production data by technology at regional level.

Is the power system as modelled in PNEC and RNC scenarios adequate to provide a reliable service under climate change effects for 2030 and 2050?

Year 2030 presented an appropriate share of renewable electricity (RES-E), with all scenarios above 80%. However, even with such high RES-E, the system was not able to contain its CO2e emissions within the limit around 1616 kt set by PNEC. In general, 2030 appeared to be adequately planned to operate under the climate variability scenarios considered, with an average cost of electricity in line with current and forecasted values. Regarding 2050, the 100% share of RES-E led to significant struggle of the system in delivering a reliable service. Although the presence of battery storage to increase flexibility, a significant amount of lost load was register in both RCP scenarios (10% of demand), and less severely in CC scenario. Such amount of lost load led to unreasonably high costs of supply, especially for RCP 8.5.

Many difficulties were encountered while building Dispa-SET-PT model. One major limitation was the absence of historical data on VRES CF at regional level, which made comparison between climate variability and constant climate scenarios affected by high uncertainty. Direct correlations between results and climate change effects were “contaminated” by the presence of curtailment, which proved being having a notable impact on VRES performances. Eventually, no interconnections between Spain and Portugal were considered, and the system was modelled as islanded.

The present study could be improved in several ways. As suggested from the sensitivity analysis, a deeper investigation on the most adequate battery capacity for 2050 would further improve the performances of the system. However, the use of a generation expansion model would be more in line with this objective. Furthermore, the introduction of realistic interconnections between Spain and Portugal to better integrate the high share of RES into the system. To do so, the modelling of Spanish electricity system would be a least requirement.

Another degree of flexibility would come from the proper modelling of pumped hydro capacity, accounting it as actual storage. Projections under climate variability of reservoir availability would have to be gathered, assumed, or computed. Finally, regional or disaggregated national historical data would help in drawing conclusions based on the results yielded by climate variability scenarios.

REFERENCES

[1] IPCC, “Global Warming of 1.5°C - Summary for Policymakers,” Masson-Delmoitte, V.; Zhai, P.; Roberts, D.; Skea, J.; Shukla, P., R.; Pirani, A.; Moufouma-Okia, W; Pidcock, R.; Connors, S.; Matthews, J., B., R.; Chen, Y.; Zhou, X.; Gomis, M., I.; Lonnoy, E.; Maycock, T.; Tignor, M.; Waterfield, T., 2018.

[2] Republica Portuguesa, “Roteiro para a Neutralidade Carbónica 2050,” in *RCM 107/2019 Resolução do Conselho de Ministros n.º 107/2019. Diário da República n.º 123/2019, Série I de 2019-07-01*, 2019.

[3] Republica Portuguesa, “Plano Nacional Energia e Clima 2030 (PNEC 2030).,” in *RCM 33/2020. Resolução do Conselho de Ministros n.º 53/2020. Diário da República n.º 133/2020, Série I de 2020-07-10*, 2020.

[4] P. Lionello and L. Scarascia, “The relation between climate change in the Mediterranean regionand global warming,” *Regional Environmental Change,* vol. 18, pp. 1481-1493, 2018.

[5] A. Paixiang, E. Hertig, S. Seubert, G. Vogt, J. Jacobeit and H. Paeth, “Present-day and future Mediterranean precipitation extremes assessed by different statistical approaches,” *Climate Dynamics,* Vols. 3-4, no. 44, pp. 845-860, 2015.

[6] P. M. Soares, R. M. Cardoso, D. C. Lima and P. M. Miranda, “Future precipitation in Portugal: high-resolution projections using WRF model and EURO-CORDEX multi-model ensembles,” *Climate Dynamics,* vol. 49, no. 7-8, pp. 2503-2530, 2017.

[7] J. R. C. (JRC), “Dispa-SET,” [Online]. Available: https://dispa-set.readthedocs.io/en/latest/index.html#.

[8] Y. P. Cai, G. Huang, Q. Tan and Z. F. Yang, “An integrated approach for climate-change impact analysis and adaptation planning under multi-level uncertainties. Part I: Methodology,” *Renewable and Sustainable Energy Reviews,* vol. 15, no. 6, pp. 2779-2790, 2011.

[9] K. Solaun and E. Cerdà, “Climate change impacts on renewable energy generation. A review of quantitative projections,” *Renewable and Sustainable Energy Reviews,* vol. 116, no. 109415, 2019.

[10] IRENA, “Planning for the renewable future: long-term modelling and tools to expand variable renewable power in emerging economies.,” Abu Dhabi, 2017.

[11] H. K. Ringkjøb, P. M. Haugan and I. M. Solbrekke, “A review of modelling tools for energy and electricity systems with large share of renewabes.,” *Renewable and Sustainable Energy Reviews,* pp. 440-459, 2018.

[12] M. Groissböck, “Are open source energy system optimization tools mature enough for serious use?,” *Renewable and Sustainable Energy Reviews,* 2019234-248.

[13] Clim2Power, “Clim2Power,” [Online]. Available: https://clim2power.com.

[14] S. Quoilin, I. H. Gonzalez and A. Zucker, “Modelling future EU power systems under high shares of renewables: The Dispa-SET 2.1 open source model.,” Pubbliction Office of the European Union, 2017.

[15] W. P. Schill, M. Pahle and C. Gambardella, “On Start-up Costs of Thermal Power Plants in Markets with Increasing Shares of Fluctuating Renewables,” Deutsches Institut für Wirtschaftsforschung, Berlin, 2016.

[16] IRENA, “Flexibility in conventional power plants.,” 2019.

[17] L. Dias, J. P. Gouveia and J. Seixas, “Interplay between the potential of photovoltaic systems and agricultural land use,” *Land Use Policy,* pp. 725-735, 2019.

[18] IRENA, “Electricity storage and renewables: Costs and markets to 2030,” 2017.

[19] ENTSO-E, “TYNDP.ENTSOE,” 2018. [Online]. Available: https://tyndp.entsoe.eu/tyndp2018/projects/projects/4.

[20] F. Amorim, A. Pina, H. Gerbelovà, P. Pereira da Silva, J. Vasconcelos and V. Martins, “Electricity decarbonisation pathways for 2050 in Portugal: A TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling,” *Energy,* vol. 69, pp. 104-112, 2014.

[21] H. C. Gils, “Assessment of the theoretical demand response potential in Europe,” *Energy,* vol. 67, pp. 1-18, 2014.

[22] J. P. S. Anjo, “Assessing the impact of demand response in the Portuguese electric system,” Instituto Superior Técnico, Lisbon, 2017.

[23] R. V. P. Figueiredo, “Renewable and resilient power systems under future climate variability - Doutoramento em Sistemas Sustentáveis de Energia,” UNIVERSIDADE DE LISBOA - FACULDADE DE CIÊNCIAS, Lisbon, 2020.

[24] IEA, “World Energy Outlook 2019,” 2019.

[25] S. Schjølset, “The MSR: Impact on market balance and prices,” Thomson Reuters Point Carbon, 2014.

[26] R. Castro, S. Faias and J. Esteves, “The cost of electricity interruption in Portugal: Valuing lost load by applying the production-function approach.,” *Utilities Policies,* vol. 40, pp. 48-57, 2016.

[27] A. Kies, B. Schyska and L. von Bremen, “Curtailment in a Highly Renewable Power System and Its Effect on Capacity Factors,” *Energies,* vol. 9, no. 510, 2016.

[28] European Commission, “Quarterly Report on European Electricity Markets, Volume 10,” Market Observatory for Energy - DG Energy, 2017.

[29] POYRY, “Portuguese Market Outlook up to 2040 - A report to APREN,” 2018.