# Assessing the impact of Demand Response in the Portuguese Electric System

João Anjo
joaosoaresanjo@tecnico.ulisboa.com
Instituto Superior Técnico, Universidade de Lisboa, Portugal
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## ABSTRACT

In order to maintain the global warming under an acceptable 2ºC increase, electricity systems need to evolve fast. Demand Response (DR) can be used as a tool, one among many, to improve the balance between demand and supply of electricity, specially in systems that rely heavily on intermittent generation, like wind, solar, hydro, wave energy, etc. Thus, it is important to understand up to what extent a countrywide system would cope with DR implementation. Using the energy-modelling tool OSeMOSYS, a model of the Portuguese electricity system is used to assess the impact of demand response implementation in the long term – up to 2050. The theoretical potential of demand response is computed to better understand the impact of its implementation on the overall system, analysing three scenarios – a business as usual scenario, a carbon-free system scenario in 2050, and a scenario without a heavy carbon emission restriction (least cost). DR impact in all three scenarios resulted in a decrease on the overall costs, on the capacity installed and in an increase of percentage of renewable capacity. Also, DR diminished the need for thermal backup capacity, reducing the capacity of biomass and natural gas power plants. Moreover, an economic analysis shows that DR takes 15 years on average to affect the average electricity cost, and that the reduction in total costs come, mainly, from avoided capacity investments. Finally, the study shows that a carbon-free system with DR implemented is less costly than a business as usual system with a 50% DR implementation.

## Keywords

Demand response; Flexible electricity demands; Energy systems modelling; Renewable energy

## 1. INTRODUCTION

In 2010, Portugal's demand for electricity was 50.5 TWh [1]. Since 2010 this number has decreased, but there is an estimated growth rate of 1.2% for OECD countries, and in the future is very likely that this demand will surpass 2010 numbers [2].

European Union has energy targets to meet in 2050, namely the cutting of 80% of carbon emissions, considering 2005 data. However, rigid policies for such a long-term period are hardly adopted, and the policies acting presently refer to 2020 targets. Portugal is ready to meet these targets for sustainability and emissions for the year 2020, but in the future, needs to do more to achieve the targets up to 2050 – however, these are not yet legally binding [3].

Portugal's electric system has already a high share of both renewable capacity and generation – 58% and 48% respectively [4]. In the electric system, the 2020 emission targets are legally binding, which means that it is compulsory to meet them. In this matter, Portugal will meet all of the targets it proposed. The EU has a vision that lasts until 2050, but this is not a legally binding agreement, meaning that member states can fall short on the targets set in the EU vision without any legitimate loss [5], [6]. In other words, there is no real incentive to achieve these new targets. On the other hand, Portugal has assumed that its individual vision for 2050 is of a total carbon-free electric system, in order to meet its share of contribution to the desired 2ºC of total global warming [7].

Due to the relation of $CO_2$ emissions with the steady rise of the world average temperature, and the consequences it can have in our way of living, fossil fuel usage for electricity generation has been highly discouraged by the majority of the world governments [8]. To facilitate co-operation and dialog on emission targets, the Paris Agreement for Climate Action was held in 2016, with 144 of total 197 parties ratifying the agreement [9]. The outcome of the convention was a common goal of maintaining the rise of the average global temperature well bellow 2º (above pre-industrial data).

In order to achieve this ambitious goal, all sectors that are responsible for emitting Greenhouse gases (GHG) must evolve towards renewable systems. In the electric system, demand side management strategies are seen as an important tool to help tackling this challenge. Pina et al. conclude that demand side strategies, with its different natures and origins, are key to achieve the sustainability of any region, even more in presence of high penetration of renewable generation. Therefore, the future power systems need to consider a big part of its design on these strategies [10].

Demand response can decrease the amount of energy losses and create more balanced energy consumption throughout each day [11]. These strategies can allow Europe and Portugal to take a step further in the problem of intermittent generation from renewable sources [12].

However, there is a need to understand how can demand side strategies - and more specifically demand response - turn this potential into reality, and in which way could it change future electric system planning.

## 2. RELATED WORK

Since the California energy crisis in 2004, demand response has been present in the US discussion of energy planning. In 2005, the US energy policy act strongly encouraged: “time-based pricing and other forms of demand response” [13]. One year later, the European Network of Transmission System Operators for Electricity (ENTSOE) issued an explanatory document on demand side management and the definition of demand-response can be derived from it:

*“Demand response (DR) is a voluntary temporary adjustment of power demand taken by the end- user as a response to a price signal (market price or tariffs) or taken by a counter-party based on an agreement with the end-user. DR during a short-term time (hours) has an impact on the system power balance and can be seen as economical optimization of the electricity demand rather than energy saving. DR during a longer period will also affect the energy balance in the power system and may also result in saving of energy.” - [14]*

The technical nature of demand response is derived from smart grid technologies. In Figure 1, the different strategies that demand response can use are explained graphically using a comparison between two profiles – a standard profile with a peak and a profile optimized with DR. The valley filling strategy uses as principle the increased usage of the installed capacity that is ready to generate electricity during most parts of the day in order to keep the balance of generation. Peak shaving decreases the need for offline capacity that is ready for dispatch, in a result of a decreased peak. Finally, load shifting uses a combination of the first two strategies [15].

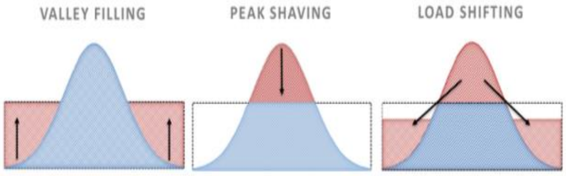

**Figure 1: Demand response strategies [15]**

As can be derived from the definition of DR, without variant tariffs or price signals, demand response is hard to implement. As Strbac states: “*It is widely accepted that some form of real-time pricing arrangements are required to efficiently allocate DSM resources and fully inform users about the value of electricity at each point in time and location*” [16]. Countless studies on this matter have been performed: Eid *et al.* give a brief and clear explanation of the several different tariffs [17]; these tariffs can be combined in order to achieve better results [18], or they can be used as a single tariff with multiple results in different regions [19], [20]. Others studies support the idea that tariffs can be implemented at different stages of the societal appropriation of demand response [21].

In a study of the potential of DR in Europe, results show that aggregating all the hourly average load reduction potential adds up to 93 GW over all countries and consumers. It also shows that the potential load reduction to annual peak load to be between 7 to 26%. Using load shedding, delaying and advancing, depending on the utility and activity, these results are reached. For example: the energy that within 2 h can be charged into the virtual storage by load reduction ranges from 47 GWh to 141GWh, and by advancing it ranges from 4 to 12 GWh [12].

Concerning more the residential sector, a study was done to optimize the electricity dispatch in a case study from a Portuguese island Corvo, in the Azores archipelago. DR is used to optimize the electric backup of domestic hot water equipment, reducing the consumption needs, and the electricity dispatch costs. Through the installation of solar thermal systems and heat pumps, and combining the island grid with DR, Corvo is able to be more energy autonomous [22].

In the industry study field, Gils relates the energy intensity of the industrial sector of a country and the overall flexible load per inhabitant, as indicators for a successful implementation of DR. The number of energy intensive industries present in a certain country is directly related to the potential of its DR deployment, reaching 69% of load reduction in Luxemburg. Energy intensive industries, such as steel (9% of total load reduction), pulp and paper (7%) and cement industries (6%) have the biggest share in the overall load reduction potential [12].

For the commercial sector, it is common to have peak-load management programs. This is more related to the high use of air-conditioning, refrigeration and lighting [16]. From the study of [12], Ireland is the country that shows highest rate of flexible loads (45%), being the main contributors the commercial ventilation (15%) and the refrigeration systems used in retail businesses.

The social effectiveness of DR programs presents one of the main barriers to its implementation. Not only economically speaking, it relates directly with social behaviour and societal appropriation of new day-to-day routines for the consumers. A study in

Australia shows that households with children in the family have almost no flexibility of participating in DR events and ToU proved ineffective. This is linked to their highly organized routine concerning activities based on children care [23].

## 3. METHODOLOGY

### 3.1. Creating an energy model on OSeMOSYS

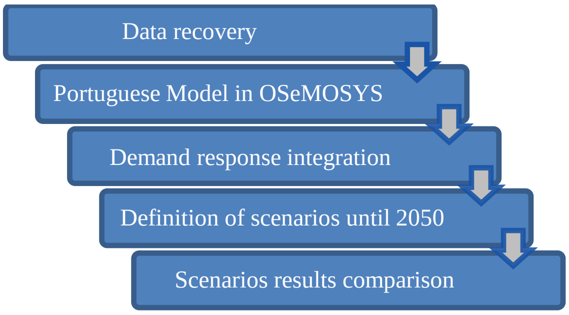

**Figure 2: Methodology of the study**

Figure 2 shows the methodology used in this thesis. The data recovered is presented throughout the case study in section 4. There, it is explained in detail the parameters and inputs used to model the system – divided in demand and supply. Equation 1 presents the objective function used.

$$\min \sum (DiscountedOperatingCost + DiscountedCapitalInvestment + DiscountedEmissionsPenalty + DiscountedSalvageValue) \quad (1)$$

### 3.2. Flexible Loads Potential

The processes suitable for DR were identified in [12], and are divided in three sectors: industrial, commercial and residential. The equations used for the calculations of the load that can be shifted for each process and sector, are presented bellow.

#### *Industrial*

In the industry sector, for every process $i$, the total annual demand $W_i$ is calculated using the annual production $C_i$, specific load for unit of production $W_i^{spec}$ and values for the percentage of usage of specific processes $s_{use,i}$.

$$W_i = C_i . W_i^{spec} . s_{use,i} \quad (MWh) \quad (2)$$

The processes suitable for DR in the industrial sector are: cement industry, wastepaper processing, air separation and paper machines.

Annual demand values for the industrial cross-sectional processes - ventilation (without process relevance) and cooling in food manufacturing - were retrieve from the country specific data present in the literature [24].

#### *Tertiary*

In the tertiary sector, for every process $i$, the total annual demand $W_i$ is calculated using the annual demand of the sector $W_{Tertiary}$ and values for the percentage of specific demand for each process $s_{demand,i}$.

$$W_i = W_{Tertiary} . s_{demand,i} \quad (MWh) \quad (3)$$

For tertiary sector the following processes were considered: cooling in food retailing, cold storages, cooling in hotels and restaurants, commercial ventilation, commercial air conditioning, commercial storage water heater, commercial storage heater, pumps in water supply and waste water treatment.

#### *Residential*

In the residential sector, for every process $i$, the total annual demand $W_i$ is calculated using the annual demand of a unit of each process (domestic appliance) $W_i^{unit}$, the number of households' $N_{HH}$, and equipment specific rates $r_i$ to model each device´s penetration.

$$W_i = N_{HH} . r_i . W_i^{unit} \quad (MWh) \quad (4)$$

The electricity demand for each device $W_i^{unit}$ has then to be calculated. For washing equipment - such as washing machines, tumble driers and dishwashers – the electricity demand is calculated in a cycle base equation, where $P_{cycle,i}$ is the power demanded in one cycle, $d_{cycle,i}$ is the duration of the cycle and $N_{cycle,i}$ is the number of cycles that are required in a year (Equation 5).

$$W_i^{unit} = P_{cycle,i} . d_{cycle,i} . N_{cycle,i} \quad (MWh) \quad (5)$$

For processes of space heating, hot water generation and air conditioning, Equation 6 is used - where $P^{unit}_{installed,i}$ is the capacity installed of every device and $n_i^{FLH}$ is the number of full load hours in a year.

$$W_i^{unit} = P^{unit}_{installed,i} . n_i^{FLH} \quad (MWh) \quad (6)$$

For residential sector the following processes are considered: freezer and refrigerator, washing machines, tumble dryers and dish washers, residential AC, residential electric water heater, residential heat circulation pump, residential electric storage heater.

In order to evaluate the impact of shiftable loads in the energy system it is necessary to implement changes in the software that account for flexibility in the demand side. For demand response implementation in OSeMOSYS, the work from [25] was used and the equations presented in this section were introduced into the existing OSeMOSYS code.

# 4. CASE STUDY

## 4.1. Supply

Table 1 shows the data used in the model for the base year of 2015. For hydro, 1.4 GW of the total 5.85 GW are pumped hydro capacity.

**Table 1: Installed Capacity in Portugal [4], [26]**

| **Residual Capacity (GW)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Heavy Fuel Oil | Hydro | Wind | Solar | Biomass | Coal | Natural Gas | **TOTAL** |
| 1.23 | 5.85 | 4.95 | 0.45 | 0.83 | 1.87 | 4.66 | **19.88** |

For coal power plants, it is assumed that all the existing power plants are fully decommissioned in the end of 2021. For gas combined cycle power plants, the decommissioning of 1.6 GW is planned for 2025. The data for the decommissioning was retrieved from [27]. The future planned power plants are part of the big investment in hydro: 0.8 GW in 2022 and 1.1 GW in 2029.

Concerning the national grid, transmission lines are assumed to be already installed. This can be an important challenge in the energy planning, however the security of supply is out of the scope of this thesis and so its barriers are not taken into account.

The costs assumptions are presented in Table 2. Note that the costs were retrieved in US dollars ($), however the results are presented in Euros (€).

**Table 2: Technology parameters [28]**

| Technology | Capital (M$/ GW) | Fixed (M$/ GW) | Variable (M$/PJ) | Emissions (mton/PJ) | Efficiency (%)[1] |
|---|---|---|---|---|---|
| **Hydro** | 2,317 | 154.49 | 1.9 | 0 | - |
| **Pumped Hydro** | 3,476 | 61.64 | 0 | 0 | 70% |
| **Wave** | 6,950 | 311 | 0 | 0 | 30% |
| **Wind Onshore** | 1,559 | 46.03 | 0 | 0 | - |
| **Wind Offshore** | 3,779 | 175.88 | 0 | 0 | - |
| **Solar** | 1,225 | 36.78 | 0 | 0 | - |
| **Biomass** | 3,959 | 195.53 | 2.19 | 0 | 35% |
| **Coal** | 2,270 | 54.79 | 1.66 | 0.247 | 45% |
| **Natural Gas** | 917 | 37.08 | 1.07 | 0.121 | 56% |
| **HFO** | 2,270 | 62.63 | 2.01 | 0.193 | 46% |

For biomass and waste power production, the $CO_2$ emissions were not taken into account, in accordance to EU policy [29].

Fuel costs considered were as presented in Table 3. For future prospects of the price of fuels, the reference used was the projections from the World Bank until 2030, and from 2030 onwards, the average percentage of increase in the forecasted years was applied. For each scenario, these projections were calculated by a factor, described in the scenarios section.

**Table 3: Fuel Costs year 2015**

| **Fuel cost (€2015/GWh)** | | | | | |
|---|---|---|---|---|---|
| Imp. Coal | Imp. Natural Gas | Imp. Heavy fuel oil | Imp. Bio | Biomass | Electricity imports |
| 6.36 | 20 | 20.5 | 37.3 | 18 | 45 |

For the hydro load factor (in OSeMOSYS capacity factor), the data was gathered from REN monthly production data. The monthly annual data from 2011 until 2016 was gathered and averaged to get monthly average values for the production of hydro, as well as percentage of pumped storage reservoir capacity. For the wind capacity factor an hourly database from the JRC of the last 30 years was used. From this database, the hourly capacity factor of one specific day of each month of the years 1985, 1990, 1995, 2000, 2005, 2010 and 2015 was gathered and then averaged. For the capacity factors computed, the average and the time-slice equivalent value are presented in the annexes [30]. The solar capacity factor was retrieved from an Internet website[2], which has the European solar PV capacity factor database CM-SAF SARAH.

In Table 4 is presented the renewable potential for the year 2050 [31], which is used to constrain the model to the availability of the resources. For solar capacity, divided in utility scale and small scale a restriction in the amount of installed capacity that could be invested in each year was restricted in order to be in line with the Portuguese legislation [32]. This results in allowing the installation of 10 MW of small-scale solar panels and of 500 MW of utility scale solar panels.

**Table 4: Renewable potential in Portugal [31]**

| Source | Unit | 2015 | 2050 |
|---|---|---|---|
| Wind On | GW | 5.034 | 7.8 |
| Wind Off | GW | 0 | 10.0 |
| Solar | GW | 0.451 | 9.3 |
| Hydro | GW | 6.914 | 9.0 |
| Wave | GW | 0 | 7.7 |
| Biomass | PJ | 0.726 | 53.1 |

The model considered Portugal as the continental part, excluding the islands of Azores and Madeira, due to the existence of independent energy systems in the islands.

Regarding operation constraints, a dispatchable reserve margin of 15% for the modelled period was assumed.

Finally, for the investments, a discount rate of 5% was assumed.

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[1] For renewable generation sources, efficiency is taken into account calculating the capacity factor. Also, the availability factor is assumed to be one, given that the maintenance operations can be performed when generation of electricity is not taking place.

[2] https://www.renewables.ninja

## 4.2. Demand

Demand input was retrieved from the ENTSOE's hourly load demand data. For better demand response implementation, demand was segmented into three sectors – industrial, residential and commercial. Analysing [33] and several other sources characterizing demand of electricity in the country, it was assumed that each sector is responsible for one third of the demand.

The average weekday load profiles for each sector are presented in Figure 3. The black line is mere representative of the daily brackets chosen (based on the residential curve) and has no numerical significance.

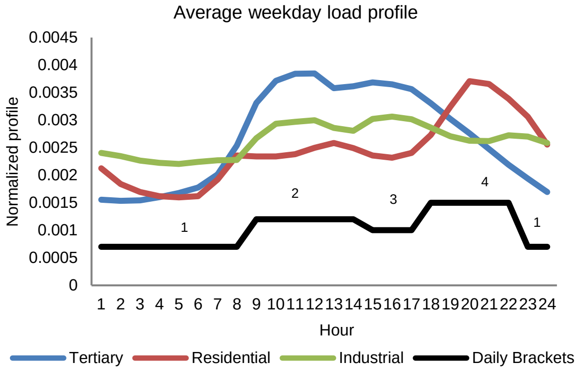

**Figure 3: Average weekday load profiles and daily brackets**

From the profiles, four time-slices per day were chosen, equalling to 96 time-slices in total – 12 months, 2 day-types and 4 daily time brackets. For each time-slice, the methodology used to calculate the profile was the same: hourly data from a typical day-type for each month averaged from 2013 to 2016. For the validation, the model results were compared with real data for the year 2015. Real data for the installed capacity and demand were used as inputs to the model.

## 4.3. Flexible load potential

In Table 5 the total demand response potential in Portugal is presented – used as 2015 data. The profiles of the processes were retrieved as follows: all industrial and tertiary profiles from [12], except commercial AC [34] and commercial storage water heater [35]; for the residential sector, freezers/refrigerators and washing machine/tumble driers/dish washers from [36], AC from [34], heat pump and electric space heater from [37] and electric water heater from [38]. The column *t-shift* represents the number of hours each process can delay or advance its load.

**Table 5: Demand response potential**

| Sector | Process | t-shift | Energy (GWh) |
|---|---|---|---|
| Industrial | Cement mils | 24 | 1243 |
| Industrial | Recycling paper processing | 24 | 216 |
| Industrial | Paper machines | 24 | 901 |
| Industrial | Air separation | 24 | 60 |
| Cross-sectional | Cooling in food manufacturing | 24 | 480 |
| Cross-sectional | Ventilation w/o process relevance | 2 | 217 |
| Tertiary | Cooling in food retailing | 2 | 1066 |
| Tertiary | Cold Storages | 2 | 147,6 |
| Tertiary | Cooling in hotels and restaurants | 2 | 213,2 |
| Tertiary | Ventilation | 2 | 2066,4 |
| Tertiary | AC | 2 | 492 |
| Tertiary | Electric water heater | 12 | 246 |
| Tertiary | Pumps in water supply | 2 | 492 |
| Tertiary | Waste water treatment | 2 | 492 |
| Residential | Freezer/Refrigerator | 2 | 2870 |
| Residential | Washing Machines, Tumble driers, Dish | 6 | 1606 |
| Residential | AC | 2 | 94,77 |
| Residential | Electric water heater | 12 | 295,2 |
| Residential | Heat circulation pump | 2 | 573,6 |
| Residential | Electric space heater | 12 | 1004,5 |

## 4.4. Scenario definition

Three scenarios were designed to better assess the model results towards 2050, considering the future of the energy system. The reference scenario (*BaU*) is generally based in the framework from EU policy and legally binding targets. Then, two other scenarios were designed using the reference scenario as base – *Low Carbon* and *Least Cost*.

The *BaU* (business as usual) scenario was based on three main sources: ENTSO-e's visions for 2030, EU´s 2016 Reference Scenario and the Energy Roadmap 2050, from the European Commission [5], [6], [39], and the projected costs for technologies are the ones provided by the document from the JRC – ETRI [28]. A limit of 1 Mton of $CO_2$ emissions is considered for 2050, as well as carbon tax of 90$/ton in the same year. The reference scenario is less optimistic than the *LowCO2* scenario. This has ambitious targets for percentage of renewable generation, emission reductions that lead to a carbon free system in 2050, as well as a steeper drop in green technologies costs and some increase in fossil fuels prices, and also a higher carbon tax – 140$/ton in 2050. The *Least Cost* scenario is more conservative in renewable deployment and more focused in economic growth, as it is the least cost-operating scenario, with $CO_2$ limits reaching 7.5 Mton in 2050 and the carbon tax fixed at 30$/ton in the last model year.

For every scenario, technology restrictions were applied: no nuclear, no new conventional Coal PP, no new Heavy-Fuel Oil PP (HFO), no new conventional open gas cycle PP and a maximum investment of 10 MW of annual residential solar PV and 500MW of utility level solar PV. Further, for renewable energy sources, the applied potential was gathered from the report [31]. Also, a maximum investment of 0.5 GW of new annual capacity from each technology was assumed.

## 5. RESULTS AND DISCUSSION

### 5.1. Scenarios without DR implementation

### *Capacity*

For the BAU scenario, there is an increase in renewable capacity from 60.9% in 2015 to 96.8% in 2050 – Figure 4. To this change there is contribution both of decommission of fossil fuel plants and installation of new renewable capacity. The total capacity installed in 2050 is 31.74 GW. In terms of decommissioning of power plants, the coal capacity becomes non-existent in 2021 and the HFO capacity slowly decreases through the first 20 years of the model period. In terms of natural gas, it shrinks its capacity from 4.66 GW in the first year to close to 1 GW in 2050. Concerning new renewable capacity: from 2029, biomass capacity increases in order to substitute some of the NG roll out of the system's thermal backup (since its non-emitting technology). Hydro and Wind-Onshore maintain their total available potential of capacity throughout the model period. Solar PV installation begins steadily when the system is in the need for new non-emitting capacity, given that hydro and wind onshore are already non-available from the year 2025. Solar reaches its full potential of 9.3 GW around the year 2045. However, substantial installation of offshore wind starts in 2039 until it reaches close to 4 GW in 2050. Also, 0.5 GW of wave energy is installed in 2050, as the overall system reaches 31.74 GW of total installed capacity.

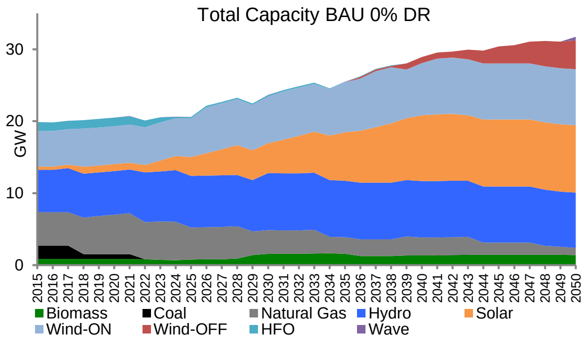

**Figure 4: Results: Total Capacity BAU 0% DR**

Comparing the results of the BAU scenario with the LowCO2 and the LeastCost scenario for the years 2015, 2030 and 2050, some differences arise from the analysis of Figure 5.

The LeastCost scenario reaches 85.9% of renewable capacity in 2050. It needs less 13% (4.5 GW) of total capacity than BAU scenario. In the year 2030 it can already be seen a difference between both scenarios – less total capacity in LeastCost that result from less biomass and onshore wind capacity. In 2050, LeastCost scenario only relies its system in four sources with the disappearance of biomass capacity and no-need for offshore wind, as in BAU. The NG capacity in the LeastCost scenario is constant during the model period, as it provides backup for renewable dispatch.

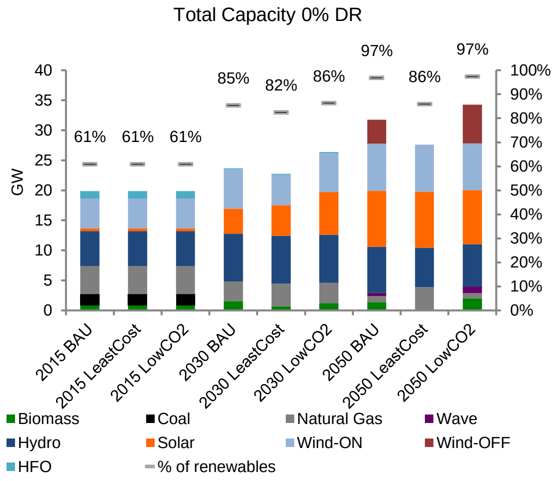

**Figure 5: Results: Total Capacity Scenarios 0% DR**

In the LowCO2 scenario in 2030, the main difference when compared with BAU is the early solar uprising that takes place in the former, with more 3 GW of solar capacity installed. The LowCO2 scenario has more 7.9% (2.5 GW) of total installed capacity when compared with BAU scenario, for the year 2050. It reaches 97.4% of renewable capacity in the same year – a value that is very close to the one in BAU. The scenario has more renewable capacity than BAU in all the sources, expect for hydro. This is due to the installation of solar in LowCO2 than in other sources until the solar potential is tapped, and when this happens offshore wind becomes more competitive, and the model installs offshore wind instead of hydro capacity.

### *Generation*

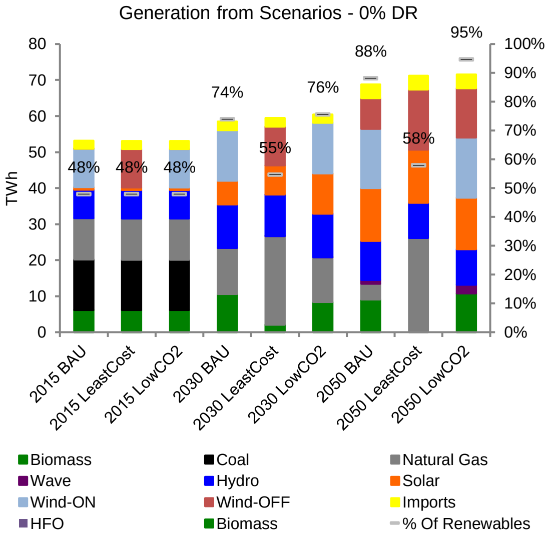

**Figure 6: Results: Generation from Scenarios 0% DR**

In the LeastCost generation from NG represents 37% of total generation (from only 14% of the total capacity). The NG generation is equivalent to all the generation from biomass, wave and offshore wind in BAU scenario. This results in only 58% of renewable generation in the last year of the model, which is explained by the competitiveness of NG due to two main factors: 1) low carbon tax that the scenario uses as input; 2) the restriction on emissions that in the LeastCost scenario allows the emissions to be up to 7.5 Mton of $CO_2$ in 2050.

In the LowCO2 scenario, generation in 2030 differs from BAU mainly on the higher output of solar generation due to higher capacity – a generation that in BAU is coming from biomass. In 2050, with the abolition of NG generation in the LowCO2 scenario, more generation is demanded from wind offshore, wave and biomass – evenly distributed among the three sources.

In relation to the overall cost of the three scenarios LeastCost is the least costly one, performing less 3.4% than the cost of BAU scenario. As for the LowCO2 scenario, it is the scenario with the highest cost, with an overall cost of more 1.9% than BAU scenario.

## 5.2. Scenarios with DR

### *Capacity*

Up to the year 2050, the total capacity is reduced with the implementation of demand response. With 50% of DR available, the total capacity of the system decreases 1.5% and with 100% DR available the total capacity is less 2.2% when compared with the BAU scenario without DR. For this difference, the main factor is the less need for backup of thermal power plants – NG and biomass. In fact, in the scenario without DR, the 2.4 GW of thermal capacity is reduced to 1.8 GW in the scenario with full DR implementation. This means that 85% of capacity reduction is due to reduction of thermal capacity. This can be explained by the flexibility provided by DR to exploit the maximum from renewable generation. Therefore, the percentage of renewables in the system increases with the implementation of DR, from 96.8% without DR to 97.5% with 50% DR implementation, and reaching 97.7% with full DR implementation.

The tendency in LeastCost scenario follows the same as in BAU scenario. The impact of DR results in a 2.1% reduction in the total system capacity in 2050. This reduction is also reached by the reduction of thermal capacity – in this case only NG, due to the non-existence of biomass capacity in 2050 for this scenario (see Figure 20). DR allows for a reduction of 0.6 GW of NG capacity. An interesting fact is that with 50% of DR implementation, 95% of the reduction in the total capacity is reached. This can be explained by an almost exhaustion of the potential of DR reached with only 50% implementation in this scenario. The analysis of the usage of the DR potential is discussed in the next sub-section.

In terms of percentage of renewables, the tendency maintains the BAU scenario as in the previous indicator. DR is responsible for an increase from 85.9% to 87.9% of the total capacity that originates from renewables.

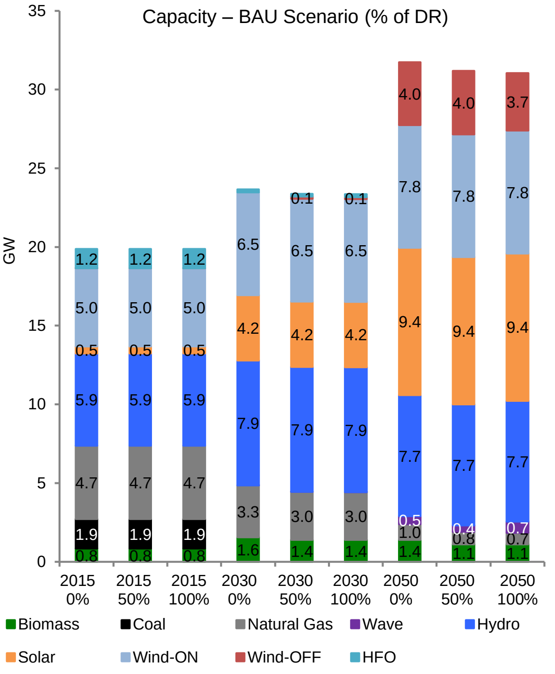

**Figure 7: Results: Capacity BAU Scenario (% of DR)**

Figure 8 presents the relative total capacity variation, within the three scenarios with different percentages of DR implementation.

In the LowCO2 scenario the total capacity is reduced with 100% DR implementation. However, with only half the DR potential, the total capacity increases (see Figure 8). Still, when looking at thermal capacity, the tendency of decreasing remains in the 50% and 100% DR results. In fact, this reduction represents the biggest reduction in thermal capacity from the three scenarios – 1 GW with 50% DR and 1.1 GW reduction with 100% DR. However, the increase in the overall installed capacity in the 50% DR case is due to more offshore wind and wave capacity. This is explained by the limited flexibility that 50% DR provides (in comparison with 100%), that allows the system to meet the demand in periods when these technologies can generate instead of having costly thermal plants (due to high $CO_2$ emission costs from NG and high variable costs from biomass). The consequence is a lower capacity to generation ratio[3] in the overall system that leads to higher total capacity when compared with 0% of DR. The

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[3] Capacity to generation ratio is an indicator that can inform about the active capacity of the total system. Typically, systems with higher shares of renewables often have lower capacity to generation ratio due to the low capacity factor of its renewable capacity.

difference with 100% DR, is that the system is able to meet more of the flexible demands in periods where the already installed capacity is capable of generating it. In terms of the absorption of renewable capacity, in this scenario DR also contributes to increase the share of renewables of the system. From 97.5% renewable capacity without DR, the system is able to have 98.4% with 50% of DR and 98.5% with full DR implementation.

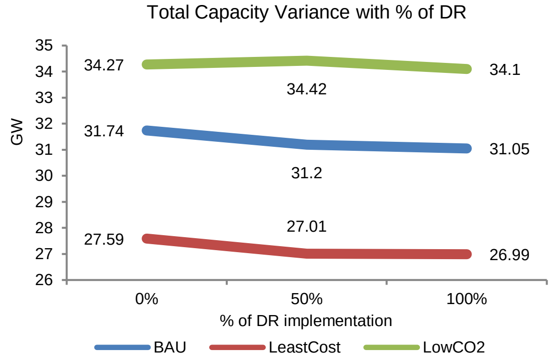

**Figure 8: Results: Total Capacity Variance with % of DR**

## Emissions

In terms of $CO_2$ emissions, DR has a substantial impact in the LeastCost scenario, but not on the remainder scenarios – due to the low-carbon nature of BAU and LowCO2. This translates in a reduction in 6% of total emissions in LeastCost scenario, but only of 0.5% in LowCO2 and of 0% in BAU. This is related with the percentage of renewable generation characteristic of each system. In LeastCost scenario, DR allows for a substitution of generation from fossil fuels to renewables – with DR, the generation in 2030 coming from renewables rises from 55% to 58%. In the other two scenarios, the DR impact only affects which renewable sources generate more electricity. These two scenarios have a strict emission ceiling that restrains the model to always emit the maximum it can in order to become less costly. Therefore, the DR impact on emissions for these two scenarios is insignificant.

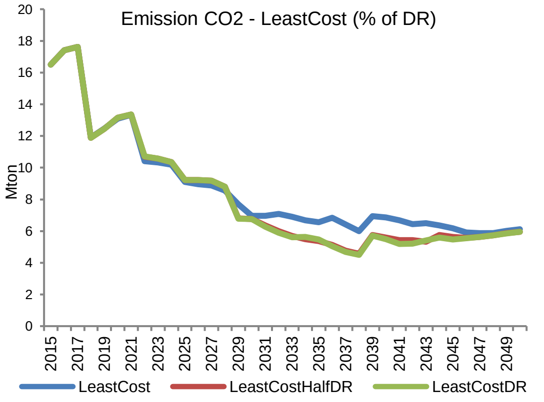

**Figure 9: Results: Emissions of CO2 - LeastCost (% of DR)**

## Load flexibility

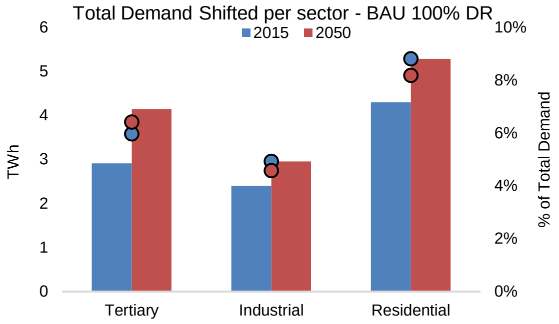

**Figure 10: Results: Total Demand Shifted per sector - BAU 100% DR**

The residential sector is the sector that provides more flexibility to the system (from 4.29 TWh in 2015, to 5.28 TWh in 2050) – it is also the sector with highest potential available. Despite, its share in the total demand experiences the biggest loss of all three scenarios between the year 2015 and 2050 – from 9% to 8% of the total annual demand.. The sector loses some flexibility through the years, mainly due to the new installation of renewables like wind, solar and in a later period wave, which can provide the system electricity during different times in contrast with the year 2015 – due to different capacity factors – where only wind has a relevant capacity share (Table 5).

The industrial sector follows the same trend, but with a smaller loss in the total share of demand, remaining its share in 5% (2.4 TWh in 2015 and 2.9 TWh in 2050). This increase in the shifted load is in line with the increase of consumption throughout the model period – around 17% from 2015 to 2050. These values show a constant use of the DR potential, from which it can be inferred that the industrial sector can prove to be more predictable in terms of DR exploitation. Industry is the sector that exploits the most of its potential throughout the model period due to the less industrial processes considered, the daily load profile each process has and the number of daily brackets that the industrial processes allow for flexibility (all except for cooling allow 1 full day of flexibility). Also, two of the processes that exploit more of its potential for the industrial sector are the two with more potential load flexibility: cement and air separation, with the latter revealing the exact percentage of potential exploited throughout the model period.

The tertiary sector is the only sector that is able to increase its share of shiftable demand in the percentage of the total demand in the model period. It increases its total demand shifted in 42% (from 2.91 TWh to 4.14 TWh) - due to the increase in the potential exploited per process. Tertiary sector presents the least potential exploitation of all the scenarios, with the load profiles of the processes being a big part of the explanation for this increase, as are mainly concentrated during the day period. With the system capable of generating more electricity during the mid-day off peak period due to changes in the installed capacity - high increase of solar that peaks the generation during mid-day – more loads can be shifted throughout the day.

**Table 6: Potential of DR exploitation in BAU scenario**

| % Potential exploited | 50% | | 100% | |
|---|---|---|---|---|
| | 2015 | 2050 | 2015 | 2050 |
| Tertiary | 76% | 69% | 56% | 60% |
| Industrial | 83% | 78% | 75% | 70% |
| Residential | 81% | 72% | 67% | 62% |

### *Costs*

With DR implementation, the overall costs are reduced. The biggest contribution arises from avoided capacity investments due to less need for installed capacity – mainly from thermal power plants. In terms of overall system costs for the model period, DR reduces the costs in all the scenarios. In BAU, DR reduces the cost in 1.67% - over 1 billion EUR. For the other two scenarios the trend is equal. In scenario LeastCost the fall in cost is 0.85% and in the LowCO2 scenario the difference reaches 2.23%.

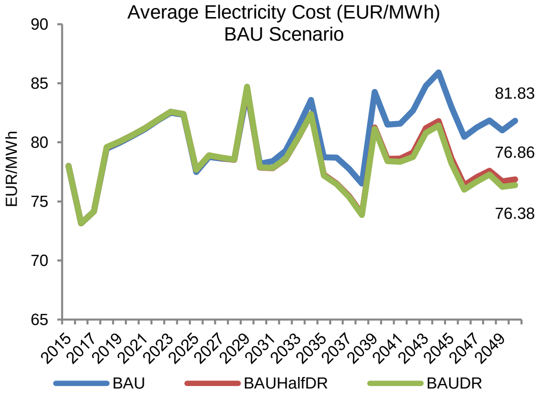

**Figure 11: Results Average Electricity Cost (EUR/MWh) – BAU Scenario**

From these results, it can be noted that the difference in costs is directly related to the installed capacity and all its associated costs. Moreover, this difference reaches higher values in systems with high share of renewable capacity, as it can be seen from scenario BAU and LowCO2. Comparing the scenario 100% DR with standard BAU scenario, the variable costs decrease 18.7%, and investment costs decrease 3.7% while fixed costs decrease 3.3%.

Also, 50% DR implementation provides 95% of the cost benefits of the total benefits available – Figure 10. The impact of adding the 50% of flexibility is even less relevant in scenario LeastCost, were 50% DR can exploit 99% of the available cost benefits. This relates to the share of generation that comes from renewables: in scenario LeastCost, 37% of the generation comes from thermal NG power plants. Hence, flexibility provided by DR is used to shift smaller quantities of loads, due to the less need for balance in the overall system. However, scenario LowCO2 had the same results as in BAU, showing that flexibility is a key tool for systems with high share of renewables.

The implementation of DR takes time for the impacts in the overall system to be felt. In this scenario it took 15 years of the model period. However, in scenario LowCO2 the impacts start to be seen in the year 2027, and interestingly in scenario LeastCost these changes only happen in 2034.

## 6. CONCLUSION

With the implementation of DR, Portugal can take a step closer in achieving a 100% renewable sources system in 2050. The importance of DR reveals itself more relevant in systems with high share of renewables already installed, but still have challenges to achieve the remaining percentages that lead to a complete 100% renewable system. These problems arise mainly from generation, and the balance that DR is able to provide throughout the sectors is a key tool in systems with these characteristics. It is patent in the results of this study that these hypotheses are verified.

From the three scenarios assessed, two of them provide results that are compliant with targets for EU's vision for 2050, and a third one provides results that can project a future with higher uncertainty, less European planning and that is more economically and less environmental driven.

The implementation of DR is transversal in reducing the cost of all three scenarios assessed. This cost reduction is related to the percentage of renewables each scenario presents, increasing in the scenarios with higher renewable capacity and generation. In the carbon free system in 2050 scenario, these cost reductions are over 1 billion EUR. However, since no costs associated with DR implementation were considered, it is senseless to analyse the economic viability of an investment in DR technology for the future.

The impact of DR in the overall system take, on average, 15 years of the model period to become relevant – in terms of capacity expansion and costs. In the analysis it can be seen that in the scenarios with higher share of renewables this impact is started to become relevant sooner - 12 years for the carbon free system scenario – than in the scenario without emission relevance (18 years).

The complexity of implementation of DR can prove a hard obstacle to energy planers, policy makers and investors. However, the results show that even with just 50% of the potential of DR implemented 95% of the cost benefits could be reach (comparing with 100% implementation). These costs arise mainly from avoided costs in installed capacity and less variable costs due to more generation from renewables without any marginal cost. This has then all the subsequent benefits in the overall system. Therefore, it can be concluded that with half the potential of DR used, a relevant part of the benefits could be available.

In the processes considered for this study, the demand sectors were divided in tertiary, industrial and residential sector. The total demand shifted from the residential sector diminished significantly within the model period, which can be inferred to be related to the less need for balancing in a system with more capacity from solar and wind sources. The tertiary sector showed the smallest percentage (in relation to the potential) of total demand shifted. An indicator that relates to the fact that load profiles of the tertiary processes are very close to the peak of demand and the majority of the processes have the lowest flexibility considered. Finally, industrial processes showed a constant and steady increase in total demand shifted and due to its profiles and flexibility in terms of time, proved to reach the highest percentage of potential for DR.

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