Demand response: a buzzword or a sustainability driver?

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Abstract

Demand response (DR) has been widely referred to as a valuable option in a smart grid environment towards efficient use of resources, with benefits both to consumers and to distribution system operators (DSO). Demand response requires automated reaction capabilities on the consumer side, by means of smart meters, to price variations and/or to DSO requests whenever demand alleviation may be beneficial to network management.

In the case of load alleviation it is arguable that it leads to a more sustainable use of resources, since the DSO is aiming at a very short-term management benefit and not at a long-term efficiency. On the other hand, it remains to be assessed whether price elasticity enabled by automatic demand response to price may be environmentally beneficial.

The present work aims at contributing to help the DSO, public authorities and society at large, to assess whether demand response based on price elasticity can reduce the environmental impact of electricity consumption, adding environmental value to the smart grid paradigm.

A methodology is presented that uses several demand response scenarios, for different penetration levels of advanced smart meters combined with time series data of the electricity generation system, applied to the case-study of the city of Coimbra, in Portugal. Several consequences are assessed, such as, for the average day, the changes on the hourly contribution of each generation technology to balance demand, as well as the corresponding changes of CO_2 emissions. The scenarios are based on hypothetical deployment levels of advanced smart meters with load management capabilities ranging from 20 % to 100 %. Simulation results show that the environmental impact of demand response strongly depends of the generation technologies that are used to follow load demand fluctuations.

Introduction

According to (WMO, 2014) the volume of greenhouse gases retained in planet Earth's atmosphere reached in 2013 a new record, the highest level since 1984. Still according to the same report, the amount of carbon dioxide (CO_2) in the atmosphere reached 396 parts per million. It is estimated that the global annual average CO_2 concentration is expected to cross the 400 parts per million threshold in 2015 or 2016.

Considering the CO_2 impact of the Energy Industries (European Union (EU) – 28 Countries 1,409 $MtCO_2e$ and Portugal 17 $MtCO_2e$ in 2012) (Eurostat, 2014), it is necessary to evaluate the possible contribution of the introduction of renewable energy technologies, smart grids and smart meters to help reduce such impact.

The present work aims to provide a contribution for the discussion of a possible methodology to assess the environmental impact of the deployment of a residential demand response technology such as the Energy Box (EB) proposed by (Livengood & Larson, 2009) in the electricity grid. The environmental impact of demand response will be assessed for deployments of the EB covering 20 to 100 % of households in a city, considering the current energy matrix framework for electricity generation in Portugal.

This article will analyze different situations that are referred to as a "case". These cases are structured in order to allow the comparison to a reference scenario (without actions of DR), considering in one hand the national energy generation matrix and in the other hand considering actions of Demand Response.

Generation of electricity

THE PORTUGUESE ENERGY MATRIX

According to REN, the Portuguese Transmission System Operator, for the average day of 2013, the generation of electricity derived from the technologies presented in Figure 1, representing SRP the Special Regime Producers.[1]

In the average day of 2013, the Portuguese energy matrix accounted with intermittent renewable generation (SRP Wind) with an impressive 32,195 MWh. SRP-Wind was followed by coal thermal power plants (30,090 MWh), SRP Thermal (23,413 MWh), Hydro – Run of River (19,403 MWh), Hydro – Dam with 17,403 MWh while imported electricity was 14,335 MWh. Below the 5,000 MWh threshold, it is possible to identify natural gas (4,293 MWh), SRP Hydro (3,659 MWh) and SRP Photovoltaic (1,212 MWh). The impact of fuel oil in 2013 was negligible, when compared to the electricity produced by all the other generation technologies.

ENVIRONMENTAL IMPACT AND EUROPEAN COMMITMENTS

The 15 EU member states at the time of the Kyoto Protocol settlement agreed to a common target for the reduction of greenhouse gas emissions of 8 % during the period 2008–2012 relatively to their emissions for the reference year of 1990. However, Portugal was allowed to increase emissions by 27 % due to the different development status. Later, the EU member states committed to a 20 % reduction in greenhouse gas emissions by 2020 (Eurostat, 2014).

In 23 October 2014, EU leaders agreed to a greenhouse gas reduction target of at least 40 % compared to 1990. This target is inserted in the 2030 framework for climate and energy policies (European Council, 2014) that also sets a target of increasing the share of renewable energy to at least 27 % of the EU's energy consumption by 2030, also increasing energy savings in 27 % during the same period.

The development over the years of this commitment at the European level and Portuguese level are represented in Figure 2.

For all those reasons, it is pertinent to assess the environmental impact that demand response may provide to help mitigate CO_2 emissions.

Household energy usage in the city of Coimbra

A proposal for estimating the hourly distribution of electrical energy for the average day for the city of Coimbra was developed by (Miguel, et al., 2013). This work provided the basis for understanding, at a city scale and in an hourly basis, what was the energy used per type of load and the type of control which was possible to exert over loads. Loads were classified as follows: type I loads can be scheduled or simply interrupted, type II, loads that can be interrupted but also allow the changing of settings, and type III, the non-controllable loads (Livengood & Larson, 2009) & (Livengood, 2011). Table 1 presents the share of loads by its specific energy service and by type of control.

The initial idea of this proposal consisted in comparing the available average daily load profiles of the residential sector, with the ability to relate reference studies that developed load diagrams with load profiles approved by the Portuguese national energy regulator (ERSE). These load profiles were complemented with statistical information specific to a city, as in Table 2, which features the city of Coimbra.

Given the differences of average consumption per city among cities, e.g., Bragança with 2,308 kWh and Porto with 3,949 kWh (PORDATA, 2013), the need for a methodology with the ability to evaluate the range of values of the power and energy that can be made available by the usage of the Energy Box was confirmed, considering that the residential energy consumption may change from city to city.

The hourly impact (percentage) of each appliance/equipment was maintained, allowing the estimation of the distribution of the electrical energy demand in the city, as in Figure 3.

This early methodology allowed the development, by the same authors (Miguel, et al., 2014), of a simulation routine that identified an approximate number of daily running cycles for the electrical loads which were selected for actions of Demand Response in the city of Coimbra, namely, the clothes washer (27.574), the clothes dryer (8.699) and the dish washer (21.179). The daily operational schedules of selected appliances were estimated using their collective contribution to the load diagram and their typical load pattern (Stamminger, 2008), using the methodology described in (Miguel, et al., 2014).

Demand Response at a city scale

The methodology for evaluating the impact at grid level of the deployment of a demand response technology was published by the authors in (Miguel, et al., 2014) . The purpose of the developed work consisted on identifying the size of the aggregated energy box resource, estimating the power that could be made available to the grid in each hour, by interrupting or postponing the start of controllable appliances, providing an equivalent service to spinning reserve. In that perspective, the identification of the period when energy consumption can be reduced was considered particularly important, as well as the periods when the rebound resulting from the switching-on of the interrupted/shifted appliances may occur.

The methodology assumed that each energy box decides whether a new schedule of operation of the equipment is more economical, depending on the current appliance cycles schedule and on the price signal, but also the constraints defined by owners regarding the possible postponements of the starting time of their appliances.

The selected or chosen method of operation of the energy box (for controllable appliances with potential of postponing operation) must consider a percentage of acceptance, which is based on the results of the tolerance or willingness of users to delay the operation of appliances according to economic criteria. These two inputs are provided by the simulation model user each time the routine is called. The additional data needed for the simulation model to operate are: the daily schedule of

1. SRP is the adopted designation for energy producers with non-dispatchable generation in Portugal, representing intermittent/stochastic generation technologies like wind and solar, waste, small hydro (S<10 MVA or in special circumstances P<30 MW), cogeneration and generation of electricity in low voltage (ERSE, 2009).

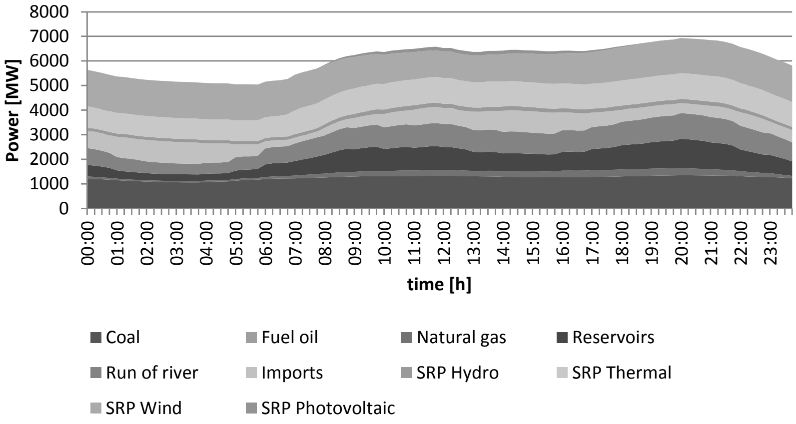

Figure 1. Evolution of the contribution of each generation technology to the Portuguese demand during an average day of 2013.

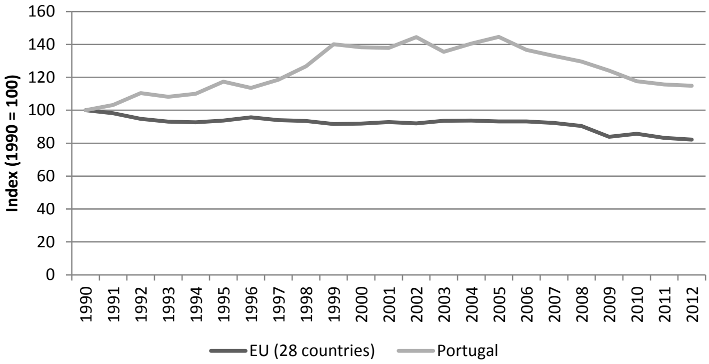

Figure 2. Greenhouse gas emissions, base year 1990 (Eurostat, 2014).

Table 1. Type of load by possibility of control (Miguel, et al., 2013).

Type of loads [%]							
Type I			Type II		Type III		
Clothes Washer	Dish Washer	Clothes dryer	Lighting	Cold Appliances	Office Equip	Entertainment Equipment	Other Applications
3.94	4.05	3.48	10.68	26.65	12.21	9.01	29.98
11.46			37.33		51.21		

Table 2. Electrical energy consumption in the City of Coimbra in the year 2010 (PORDATA, 2013).

City	Average Electrical Consumption per household [kWh/year]	# Electricity Consumers	Total domestic consumption (kWh]
Coimbra	2,966.10	76,642	227,327,836.20

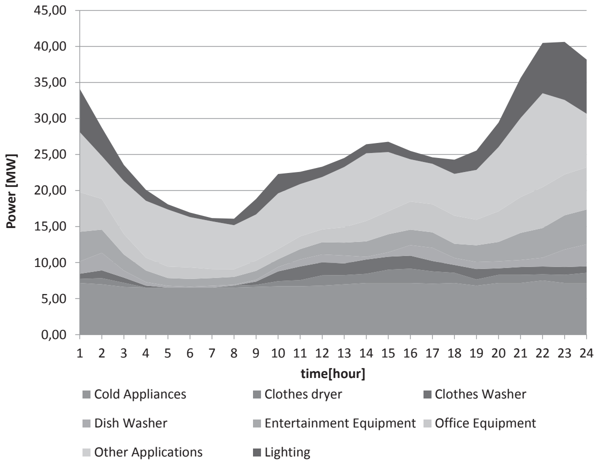

Figure 3. Estimation of the distribution of electrical energy for the average day for the city of Coimbra with loads represented by decreasing regularity of the standard deviation (Miguel, et al., 2013).

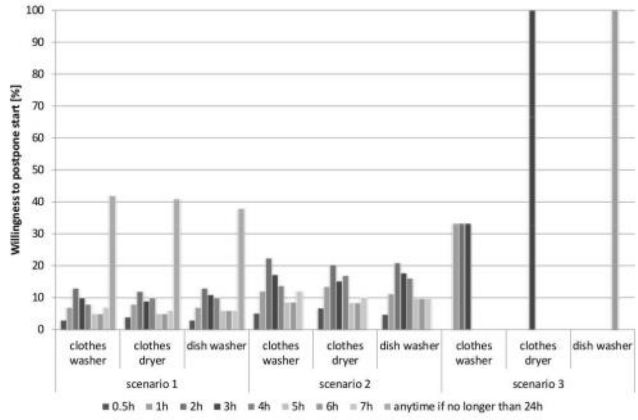

Figure 4. Willingness to postpone start [%] for the considered appliances, scenario 1 based on (Mert, 2008), scenario 2 adapted from (Mert, 2008) without the possibility to postpone start 24 h, scenario 3 adapted from (Jamasb & Pollitt, 2011), (Miguel, et al., 2014).

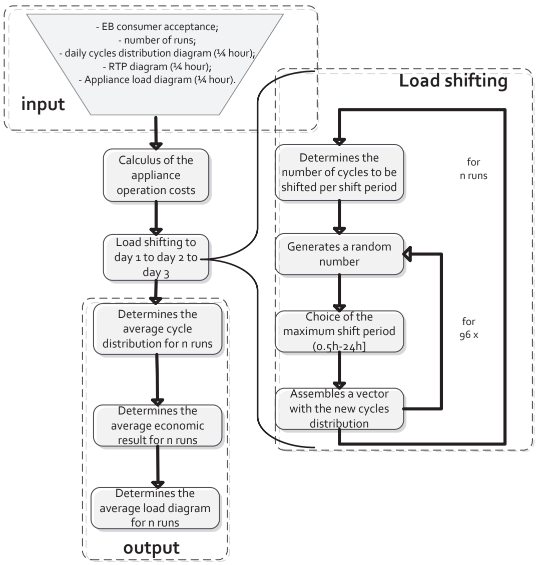

Figure 5. Structure of the simulation routine for demand response (Miguel, et al., 2014).

operation of the chosen appliances, the day ahead electricity prices and the load diagram corresponding to a single operating cycle of each appliance type. Since the operation of the energy box follows a price signal, load shifting was based on the spot price for an average day of 2012 according to the Iberian Energy Derivatives Exchange (OMIP website) (OMIP, 2013). This allows the calculation of the appliance operational cost for all the possible cycles starting at the beginning of each quarter-hour in a three days period.

The consumption was delayed/rescheduled according to the willingness to postpone the starting time of appliances, following the energy price (which can ultimately include also renewable energy preferences or other preferences to be monetarily valued).

To represent the individual decisions made by each Energy Box owner, regarding how long a delay is allowed in the operation of a certain end-use (0.5 h, 1 h, 2 h, 3 h to 24 h), a Monte-Carlo based procedure was used, generating possible decisions to each of the considered energy boxes in each run. This kind of procedure tries to reproduce the collective behaviour of consumers, based on the probability distributions reported in (Mert, 2008) and (Jamasb & Pollitt, 2011), associated to the choice of each of the possible settings. In Figure 4, three scenarios of hourly consumer tolerances are presented, which were used to postpone the start of appliances.

Figure 5 presents the structure of the developed routine. The model uses three consecutive days in order to obtain a clean outcome of the central day, avoiding first-day and last-day effects that would be minimized in the long run.

The total number of load cycles of the appliances is maintained during the three day simulations. The procedure for determining the number of loads to be shifted, considers the rate of deployment of the energy box and the amount of time that consumers are willing to allow the postponement of the start of the specific operation of a specific appliance.

In Figure 6 an example is shown of a 20 % deployment of the EB at the city of Coimbra, with the three distinct consumer tolerances for postponing the start of appliances. The maximum power that the aggregated energy boxes may alleviate in each quarter-hour may be assessed by the difference between the reference demand and the minimum demand obtained in the simulations. The rebound that can occur is also obtained by the difference between the maximum demand obtained in the simulations and the reference load diagram. The results presented in Figure 7 show that the aggregated resource may deliver around 700 kW between 12:30–13:30 and between 18:30 and 22:30, representing a maximum of circa 3 % of the demand on that period. Results also show that a significant rebound may occur unless the switching on of the loads is carefully scheduled (Miguel, et al., 2014). This rebound is caused by abrupt load restoration, but can be avoided through some gradual procedure, eventually using a

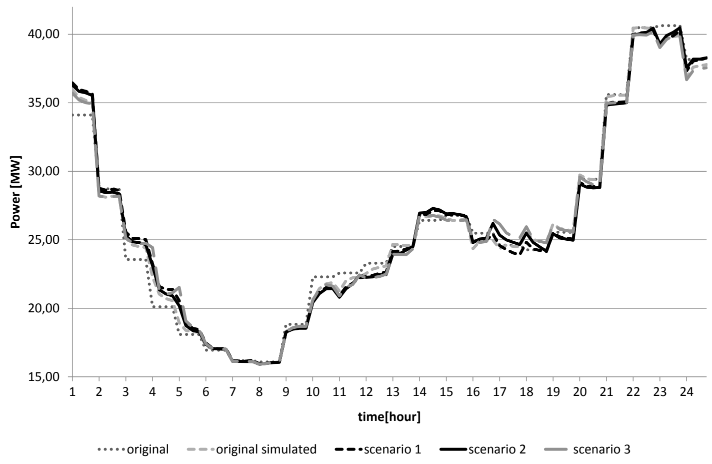

Figure 6. Example of a 20 % deployment simulation of the Energy Box in the city of Coimbra, with three scenarios with distinct consumer tolerances (Miguel, et al., 2014).

Figure 7. Range of the power delivery and rebound for a 20 % deployment of the Energy Box in the city of Coimbra (Miguel, et al., 2014).

Table 3. Maximum and minimum power verified in the load diagrams at a certain time (Miguel, et al., 2014).

		original	original simulated	20 % EB Scenario 1	20 % EB Scenario 2	20 % EB Scenario 3
Maximum diagram power	Power [MW]	40.63	40.50	40.32	40.47	40.18
	Occurred at :	23 h 00 m	22 h 15 m	22 h 45 m	23 h 45 m	22 h 45 m
Minimum diagram power	Power [MW]	16.09	15.92	15.96	15.92	15.92
	Occurred at :	8 h 00 m				

peak minimisation approach. In the absence of this cautionary approach, a new peak load may occur, as shown in Figure 7.

This diagram accounts for a maximum power of 40.63 MW and a minimum power of 15.92 MW, as can be confirmed through the reading of Table 3.

Assessing the environmental impact of demand response

The method for assessing the environmental impact of demand response, considered, for simplifying reasons, the quarter-hour contribution of each energy source to the electricity generation system for the average day. In this case, the information was provided by REN the Portuguese Transmission System Operator. The data consisted in a spreadsheet for every day of the year 2013, segregated by quarter-hour, with the discrimination of the power contribution of each energy source to the generation diagram.

As stated previously, a methodology was developed by the authors (Miguel, et al., 2014) to evaluate the impact of the deployment of the EB in the electricity grid under different scenarios and deployment rates. This provided a tool to rehearse demand response actions, using three possible consumer tolerances for postponing the start of appliances and a set of daily price prototype diagrams representing a year. Such prototypes were the output of a clustering exercise applied to the price dia-

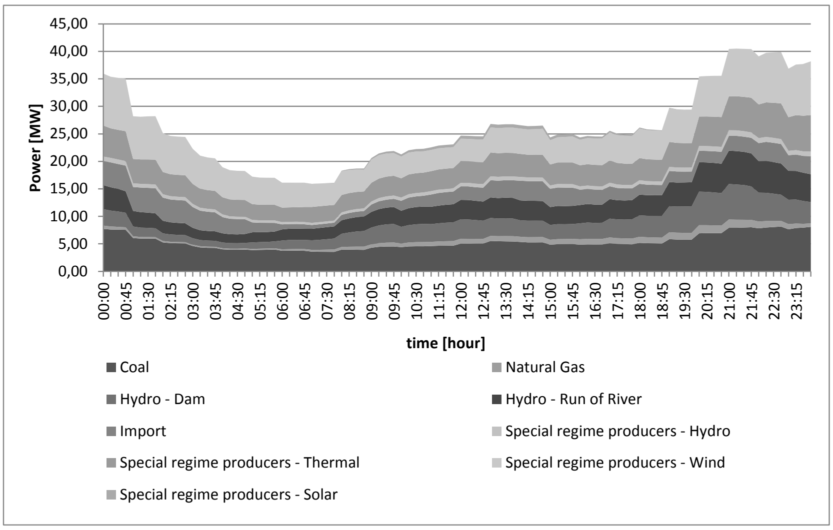

Figure 8. Average load diagram of the city of Coimbra, with the quarter-hour contribution of each energy source.

grams of a whole year, using both a hierarchical method (HM) and competitive neural networks (CNN), each clustering method providing five price prototype profiles. The data regarding the hourly impact of each energy source for the average day, combined with the simulations of the EB impact, provided a framework of a total of twelve simulations with three distinct consumer tolerance values, in the following manner: one simulation uses the average price day diagram for the year of 2012, a second uses the average price day diagram from October 2012 to September 2013, five used price prototypes extracted from the HM and, finally, five used price prototypes extracted from the CNN method. The combination between simulations (12) and scenarios (3) with five deployment rates, from 20 % to 100 %, accounted for a total of 180 simulations.

The environmental impact of demand response was estimated using the average share of load by each generation technology at each quarter of an hour in the average day.

The average contribution of each generation technology to the load diagram is represented in Figure 8.

The method for assessing the demand response environmental impact is represented in Figure 9. In order to assess such environmental impact, the output or the contribution of renewable energy sources (Hydro-Run of River, SRP-Hydro, SRP-Wind and SRP-Solar), plus Imported electricity and SRP-Thermal is conserved equal to the average day simulation. The generation technologies and fuels that were affected by demand response actions were the following:

- Hydro-dam, as this is usually the technology that react to demand peaks due to its fast response;
- Combined cycle gas turbine (CCGT), due to its increasing weight in the generation system and its higher generation efficiency;
- Coal based steam turbine, due to usual high share of usage in the generation system, assuming that it is the most economic generation technology;
- Combined coal based steam turbine and CCGT, using their respective shares in each quarter-hour of the average day.

The variations reflect changes in the composition of the generation mix resulting from demand response. Thus, the new generation technology contributions are redefined, ensuring that the required power is supplied to the electricity system under the modified load conditions.

Emissions can be calculated applying appropriate conversion factors to the energy outputs of the generation technologies at stake.

CALCULATING THE REFERENCE OF THE ENVIRONMENTAL IMPACT OF DEMAND RESPONSE

Table 4 presents the contribution of each energy source for supplying electricity to the city of Coimbra for the average day.

In the average day of 2013, SRP Wind is the biggest contributor of the electricity generation system with 22.29 %. Coal thermal power plants are responsible for 20.58 % of the energy supplied in the city of Coimbra. Above 10 % share, electricity is provided through SRP-Thermal (16.00 %), Hydro-Run of River (13.15 %) and Hydro-Dam (11.88 %). Below 10 %, imported electricity (9.97 %), natural gas (2.91 %) and SRP-Hydro (2.49 %) and SRP-Solar with 0.73 %.

Table 5 presents the CO_2 emissions for the original simulated scenario, based on (DRE, 2008) and considering a thermodynamic efficiency of 40 % for generating electricity using coal and 55 % for generating electricity using a CCGT (Eurelectric, 2003) (World Energy Council, 2013). Such thermodynamic efficiency mean that the calculated CO_2 emissions per energy unit for coal is of 236.25 $kgCO_2e/GJ$ and for CCGT is 116.54 $kgCO_2e/GJ$.

CASE 1 – USING GAS AS THE TARGET FOR ACTIONS OF THE ENERGY BOX

In the present section the use of natural gas (CCGT) to compensate DR fluctuations is compared with other technologies. Table 6 presents the energy results.

In Table 6, it is perceivable that the standard deviation of simulations with energy decrease is higher than in simulations with energy increase, both in coal and in natural gas.

By using CCGT a significant number of simulations led to a reduction in the emissions, even if the total consumption was

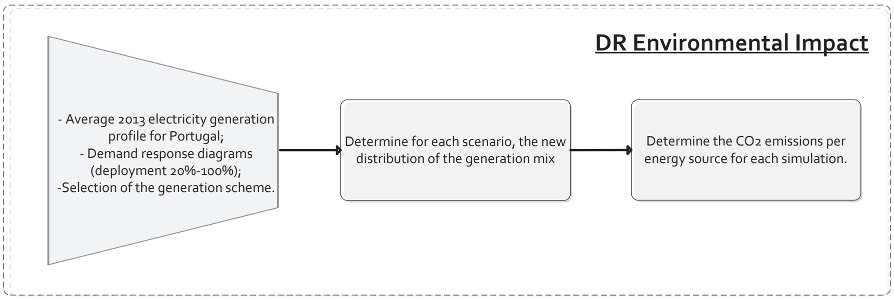

Figure 9. Method for assessing the energy transfer and CO_2 changes due to demand response actions.

Table 4. Estimation of the contribution of each electricity generation technology for the average day of the city of Coimbra in the original simulated scenario (without DR) in [GJ/day].

	Energy [GJ/day]									
	Coal	Natural Gas	Hydro – Dam	Hydro – Run of River	Import	SRP – Hydro	SRP – Thermal	SRP – Wind	SRP – Solar	Total
Original simulated	461.35	65.12	266.26	294.72	223.58	55.76	358.74	499.55	16.38	2,241.45

Table 5. CO_2 emissions for the original simulated scenario.

	Emissions [tCO_2e/day]		
	Coal	Natural Gas	Total
Average 2013 profile	108.99	7.59	116.58

Table 6. Statistical results for simulations of Demand Response for the city of Coimbra with gas generation technology used to compensate power demand fluctuations.

	Energy [GJ/day]					
	Increase in load demand			Decrease in load demand		
	Coal	Natural Gas	Total	Coal	Natural Gas	Total
Mean	442.61	85.21	2,242.80	445.73	79.71	2,240.42
Standard Error	1.39	1.43	0.09	3.05	2.97	0.17
Median	445.64	82.09	2,242.62	456.73	69.6	2,240.69
Standard Deviation	16.68	17.17	1.03	18.06	17.58	1.01
Variance	278.22	294.9	1.06	326.12	309.09	1.02
Minimum	399.47	65.13	2,241.46	409.52	63.98	2,237.27
Maximum	461.35	128.52	2,245.66	461.35	114.47	2,241.43
Number of simulations	145			35		

Table 7. Statistical results for simulations of Demand Response actions for the city of Coimbra, using gas generation technology to compensate power demand fluctuations.

	Emissions [tCO_2e/day]					
	Emissions increase			Emissions decrease		
	Coal	Natural Gas	Total	Coal	Natural Gas	Total
Mean	108.99	7.64	116.62	103.99	10.17	114.16
Standard Error	0	0.01	0	0.31	0.16	0.16
Median	108.99	7.63	116.62	104.38	9.98	114.44
Standard Deviation	0.02	0.04	0.02	3.89	1.96	1.94
Variance	0	0	0	15.13	3.84	3.78
Minimum	108.89	7.59	116.58	94.37	7.46	109.35
Maximum	108.99	7.78	116.67	108.99	14.98	116.58
Number of simulations	26			154		

Table 8. Case 1, generation technology shares, in %.

	Generation technology shares, in %	
EB deployment [%]	**Coal**	**Natural gas**
original simulated	20.58	2.91
20	20.58	2.91
40	20.39	3.11
60	19.91	3.61
80	19.30	4.23
100	18.65	4.90

increased. This was due to the replacement of coal based electricity by CCGT based electricity as a result of DR.

These results are understandable as in larger deployments of the Energy Box there is a shift in the share of technologies, with coal reducing from 20.58 % in the original simulated scenario to 18.65 % in a 100 % deployment scenario, while the share of natural gas rises from 2.91 % to 4.90 %. In cases of load demand requiring a power reduction higher than the power provided by natural gas, the remaining value was subtracted to the coal generation technology in order to maintain the balance between supply and demand.

Other findings:

- No simulation with a net energy consumption reduction resulted in increases in CO_2 emissions;
- In 82 % of simulations with a consumption increase, a decrease in CO_2 emissions was verified.

CASE 2 – USING COAL AND GAS AS THE TARGET OF THE ENERGY BOX ACTIONS

The present section presents the possibility of using coal and natural gas technologies in combination to compensate DR fluctuations. The new contribution of each of these two technologies will linearly reflect its share, considering the original contribution, thus maintaining percentage share while determining the new quarter-hour power contribution of the generation mix. In Table 9 the simulations regarding the load demand of DR are presented, compensated by coal and natural gas generation technologies.

Table 10 presents the results of the simulations regarding the emissions of CO_2. Considering the difference of scale between the shares of coal and natural gas, there is a natural trend towards the increase of CO_2 emissions in simulations, especially, due to the increase of the contribution of coal, 172 simulations had an increase in CO_2 emissions, while only 8 simulations showed a CO_2 emissions decrease.

Table 11, confirms what was claimed earlier, namely the slight increase of CO_2 emissions due to the increase of the contribution of coal and the decrease of the contribution of natural gas, for larger deployments of the energy box.

Other findings:

- In 77 % of simulations with a decrease of energy consumption, an increase in CO_2 emissions is verified;
- In 16 % of simulations with an increase in CO_2 emissions, a decrease in energy consumption occurs;
- In all simulations with an energy consumption increase, an increase in CO_2 emissions occurs.

Table 9. Statistical results of Demand Response for the city of Coimbra, with coal and gas generation technologies used to compensate power demand fluctuations.

	Energy [GJ/day]					
	Increase in load demand			Decrease in load demand		
	Coal	Natural Gas	Total	Coal	Natural Gas	Total
Mean	465.25	62.60	2,242.80	463.66	61.78	2,240.42
Standard Error	0.18	0.13	0.09	0.31	0.35	0.17
Median	465.02	62.96	2,242.62	462.98	62.39	2,240.69
Standard Deviation	2.16	1.53	1.03	1.81	2.10	1.01
Variance	4.68	2.35	1.06	3.27	4.42	1.02
Minimum	462.13	58.36	2,241.46	461.56	57.56	2,237.27
Maximum	472.35	64.73	2,245.67	468.65	64.38	2,241.43
Number of simulations	145			35		

Table 10. Statistical results of simulations of Demand Response actions for the city of Coimbra, with coal and gas generation technologies used to compensate power demand fluctuations.

	Emissions [tCO_2e/day]					
	Emissions increase			Emissions decrease		
	Coal	Natural Gas	Total	Coal	Natural Gas	Total
Mean	109.87	7.28	117.15	109.22	7.24	116.47
Standard Error	0.04	0.01	0.03	0.06	0.07	0.02
Median	109.84	7.32	117.10	109.13	7.27	116.47
Standard Deviation	0.51	0.2	0.38	0.17	0.21	0.07
Variance	0.26	0.04	0.15	0.03	0.04	0
Minimum	109.13	6.71	116.61	109.04	6.83	116.38
Maximum	111.59	7.54	119.03	109.55	7.44	116.56
Number of simulations	172			8		

Table 11. Case 2, generation technology shares, in %.

	Generation technology shares, in %	
EB deployment [%]	**Coal**	**Natural gas**
original simulated	20.58	2.91
20	20.63	2.86
40	20.68	2.82
60	20.73	2.78
80	20.79	2.75
100	20.84	2.70

Table 12. Statistical results for simulations of Demand Response for the city of Coimbra, with hydro-dam generation technology used to compensate power demand fluctuations.

	Energy [GJ/day]					
	Increase in load demand			Decrease in load demand		
	Coal	Hydro – Dam	Total	Coal	Hydro – Dam	Total
Mean	461.08	267.88	2,242.8	460.88	265.7	2,240.42
Standard Error	0.08	0.12	0.09	0.19	0.17	0.17
Median	461.35	267.49	2,242.62	461.35	265.94	2,240.69
Standard Deviation	0.97	1.46	1.03	1.11	0.99	1.01
Variance	0.94	2.12	1.06	1.23	0.99	1.02
Minimum	454.76	266.27	2,241.46	457.26	263.70	2,237.27
Maximum	461.35	274.38	2,245.66	461.35	268.60	2,241.43
Number of simulations	145			35		

Table 13. Statistical results of Demand Response actions for the city of Coimbra, with hydro-dam generation technology used to compensate power demand fluctuations.

	Emissions [tCO_2e/day]			
	Emissions lowered to the level of the average day		Emissions decrease	
	Coal	Total	Coal	Total
Mean	108.99	116.58	108.67	116.26
Standard Error	0	0	0.07	0.07
Median	108.99	116.58	108.86	116.45
Standard Deviation	0	0	0.41	0.41
Variance			0.17	0.17
Minimum	108.99	116.58	107.44	115.03
Maximum			108.98	116.57
Number of simulations	140		40	

Table 14. Case 3, generation technology shares, in %.

	Generation technology shares, in %		
EB deployment [%]	Coal	Natural gas	Hydro – Dam
original simulated	20.58	2,91	11.88%
20	20.58	2.90	12.02%
40	20.58	2.90	12.04%
60	20.57	2.90	12.05%
80	20.56	2.90	12.07%
100	20.51	2.90	12.12%

CASE 3 – USING HYDRO-DAM AS THE TARGET OF THE ENERGY BOX ACTIONS

In the following section, the results regarding the possibility of using hydro-electricity from dams to compensate load demand fluctuations due to actions of DR are represented.

Table 12 show results regarding the energy distribution of coal and hydro-dam technologies. It is possible to verify that while in the energy increase scenario, the standard deviation of hydro-dam is higher than for coal, the standard deviation of hydro-dam in the situations where energy consumption increase occurs is lower than for coal generation technologies. Similarly, to what happened in the case where natural gas was used to compensate load demand, in certain simulations, maintaining supply and demand balance required a reduction of the coal based generation output.

The use of an emissions-free source as hydro-dam to compensate the actions of the EB results in a neutral output, maintaining the level of emissions of the original supply to the city. The results from simulation are shown in Table 13.

Despite the number of simulations with lower CO_2 emissions (below the average value) being not meaningful, it is perceivable from Table 14 that the impact of coal and natural gas technologies is slightly lower, while the impact of hydro-dam is slightly higher.

Other findings:

- In 71 % of simulations with energy decrease, CO_2 emissions did not surpass the average emissions from the original simulated scenario;
- In 81 % of simulations with an increase in energy consumption, emissions were lowered to the level of the average day.

Conclusions

Demand response is not per se a tool for reducing CO_2 emissions. It strongly depends of the generation technologies that support the electricity system (energy matrix), and of which generation technologies will be used to compensate load demand fluctuations caused by actions of DR.

In the case of using gas as the target of the EB actions it can be highlighted that a 20 % deployment of the EB does not produce a significant impact on the energy mix, gas and coal keeping their original shares. However, in 82 % of the simulated days having a higher energy consumption than the average day, CO_2 reductions were obtained, from the original value of 116.58 tCO_2e/day to a minimum of 109.35 tCO_2e/day (approximately 6 % reduction in CO_2 emissions).

By using coal and gas as the target of the EB actions and maintaining their original quarter-hour shares, a constant increase was verified in the share of coal, and a constant decrease of the share of gas for compensating the actions of the EB. Thus, a generalized increase in CO_2 emissions occurs when the current quarter-hour shares of such generation technologies are maintained to compensate DR actions. This is easily verifiable because in 77 % of simulations with energy consumption below the average day, an increase in CO_2 emissions was verified.

The use of electricity generated in dams as the target of the EB actions is also an effective way to avoid CO_2 emissions increase. In fact in 81 % of simulations with higher energy consumption than the average, emissions were levelled to the average day value. However an effective decrease of emissions is harder to obtain: in those cases where a CO_2 reduction occurred, emissions were reduced from 116.57 tCO_2e/day to 115.03 tCO_2e/day, which corresponds to a maximum possible reduction of 1.32 %.

Dispatch criteria described in section "Case 1" lead to the replacement of gas for coal whenever total load affected by DR actions becomes less than the previous supply level of coal and gas together, as in the base case. The uptake of part of the coal based supply by gas-based supply leads to a decrease of CO_2 emissions (reaching a minimum of 109.35 tCO_2e/day), which is not so noticeable when hydroelectricity is the only option besides coal, the latter approximately maintaining the base case share of supply and the corresponding emissions (reaching a minimum of 115.03 tCO_2e/day).

Future results of appliance-focused testbed projects aiming at the identification of price elastic behaviour of electricity demand will hopefully lead to a deeper understanding of the relation between demand response and the use of renewable electricity supply. Such understanding may provide the basis to evaluate DR under different circumstances, crossing demand and generation capacity and their respective variations during the year.

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