Electrical Power and Energy Systems 156 (2024) 109747

Contents lists available at ScienceDirect

International Journal of Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

System planning with demand assets in balancing markets

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ARTICLE INFO

Keywords:
Demand response
Reserves
FRR
Optimization
Flexibility

ABSTRACT

Balancing markets will become more and more relevant with the increased volatility in the electricity system due to the increase in the renewable quota. New policies are paving the way for customers flexibility participation as demand response in reserve products. This paper contributes with an assessment of the impact of demand response participation in the reserve market when planning the electricity system's operation and investment in new technologies. The model used has been conveniently upgraded and a set of scenarios have been raised to conduct the analysis. The residential and services sectors' consumption for heating, cooling, hot water, and electric vehicles are considered as sources of flexibility. Each one has their own modeling to represent their nature. Main findings show that demand response receives and offers more benefits for the system on the wholesale market than in balancing services, although their participation in them is quite relevant. This is due to the decrease in firm capacity investment needs thanks to reducing systems' peak technologies and the decrease of spillages from renewables. Additionally, increasing demand response percentages in the systems lead to cost reduction. However, there is a limitation associated with an increase of CO2 emissions due to the usage of existing polluting technologies to avoid investments in storages. Finally, flexibility providers are compared to determine their flexible capabilities.

1. Introduction

The evolution of power systems and electricity markets is experiencing an increase in renewable resources, creating the need for flexible resources such as batteries and demand assets or the reinforcement of interconnections. European directives (Directive 2019/944) [1] and policies such as the Clean Energy Package [2], are paving the way to extend energy customers flexibility, capability of shifting consumption, by taking part in a demand response (DR) program. Consequently, this paper explores the role that DR can fulfill within the entire electricity system. It addresses technology investment planning and operation by considering DR full potential, enabling its participation in wholesale and balancing markets. Besides, to be able to limit DR potential and avoid overestimating it, this work counts with a detailed representation of the different demand sectors, which are the residential, services and industrial sectors, and disaggregated consumption categories, between heating and cooling (H&C), domestic hot water (DHW), electric vehicle (EV) and others. The purpose of this analysis is to compare the sources of DR and assess their influence on investment and operational decisions, determining when DR can be effectively employed in each commodity, whether in wholesale or balancing markets.

Full deployment of DR, could lead to significant balancing savings for Europe, between 43 % and 66 % of balancing costs, depending on the country and the balancing capacity needs [3]. These studies[4,5], demonstrate cost reductions ranging from 15 % to 21 %, primarily through operational cost reductions, achieving a more pronounced cost reduction when DR participates in reserve markets. By managing the full availability of DR specific sources [6], economic savings can rise to 14 % of annual costs solely by providing downward reserve. When analyzing Europe as a whole, total system costs can be reduced by 17 %[7]. Furthermore, 30 % savings are estimated for the Spanish system when modeling flexibility as 8 % of the total demand, without considering special constraints for the use of this flexibility [8]. DR current implementation in European countries is still very small [9–11] and there are still some regulatory and social barriers that should be faced [12,13]. Therefore, to foster all DR possibilities development in the different countries, this paper studies the effect of considering DR participation in balancing services. This paper assesses different flexible demand penetration quantities, with a more conservative range estimated for system cost savings due to limitations in DR movements. This study also compares the operation of H&C, DHW and EVs to understand how their flexibility interacts with the electric power system. Although more

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https://doi.org/10.1016/j.ijepes.2023.109747
Received 6 July 2023; Received in revised form 20 November 2023; Accepted 21 December 2023
Available online 7 January 2024

flexible demand categories could have been considered, such as refrigeration and compressed air, they were not introduced to facilitate understanding the model.

In [14], district heating systems are assessed as a source of flexibility, providing all balancing services at a European level. The study determines that flexibility sources have a higher potential in providing Automatic Frequency Restoration Reserve (aFRR) service due to constraints on their ramping periods, almost double the Manually Frequency Restoration Reserve (mFRR) potential and four times the Frequency Containment Reserve (FCR), potential. The challenge of relying on DR participation in FRR services has been handled throughout literature from different points of view. In [15], DR participation in balancing markets is analyzed from an aggregator perspective. Moreover, [16,17] value DR contribution to balancing services from a building perspective. Finally, demand participation in reserves has also been analyzed from the DSO and TSO controller perspective, solving frequency and voltage regulation network issues [18,19]. For this case study, balancing services will refer only to aFRR service with up and down considered separately, and it will be analyzed from a system perspective, with investment planning and operation optimization.

Consumption in the residential and services sectors is where customers flexibility is most underutilized and where its exploitation presents the most opportunities[20,21]. This paper focuses on assessing the impact of DR provision from the residential and services sectors', which has not traditionally been economically viable [20]. However, European grants for electrification in these sectors [22], come with an increase in customers flexibility potential and hence, profitability. In particular, Spain has developed measures to incentivize electrification for heating and cooling services [23] and for overland transportation [22,24]. Furthermore, technological advances facilitate the remote controllability of end-use energy demand to be able to participate in electricity system services [25]. Table 1 compiles prior models that have assessed the participation of DR in balancing services. The columns within the table highlight key characteristics of these models, revealing the novelty of the model presented and employed in this paper. First, the markets in which DR can participate are indicated, distinguishing between the wholesale market and various balancing services, including FCR, FRR [26], and Replacement Reserve (RR). Subsequently, the sectors within which DR has been studied are specified, distinguishing among residential (RES), commercial (COM) and industrial (IND). Additionally, the modeled disaggregated consumption categories capable of providing DR are identified, considering only H&C, DHW and EV classification. Furthermore, it is indicated whether any specific constraints have been applied to restrict DR potential. Finally, the last column refers to the type of model under consideration, indicating if the model applies to the whole system and in case it does whether both operational (OPER) and investment (INV) optimization are considered.

From the literature review it can be concluded that the modelling of DR participation in the reserves market from a system overview of behind-the-meter assets from the residential and services sectors has not been extensively studied. Therefore, this paper contributes with a comprehensive generation and storage expansion planning model, conveniently upgraded to allow DR participation in both wholesale and reserves markets constraining the demand assets to better represent their consumption nature. Through the analysis conducted, this paper also contributes to identifying which DR assets supply more energy and in which market (wholesale or reserves) they are best suited to participate. Finally, the analysis also reveals that increasing demand response percentages in the systems lead to cost reduction. However, there is a limitation associated with an increase of CO2 emissions due to the usage of existing polluting technologies to avoid investments in storages. This finding has policy implications since it shows that although demand response leverages existing infrastructure, it should be combined with new storage investments (against the minimum cost alternative) to deal with the increase of emissions.

Different scenarios have been defined to assess the role of these demand assets providing reserves and their impact on generation and storage investment planning and on electricity system costs and emissions using the Spanish system as a reference. The rest of the paper is organized as follows. Section II, describes the upgrades in the formulation of the model to include the reserves market and demand participation in providing balancing services. Section III gathers the input data required to run the model and perform this analysis for the Spanish system in 2030. An analysis and description of results are presented in Section IV. Section V summarizes the relevant conclusions and proposes some future research lines to enrich this study.

2. Model formulation

The tool used to develop this study has been an operation and expansion planning model, named SPLODER, with the convenient upgrades. The initial version of the model was fully described in [44]. Some other upgrades are presented in [45–47] to include policy constraints and new storage technologies that can compete with flexible

Table 1
Optimization models with DR participation in balancing services.

Source	Energy market	Balancing services			Sector with DR			DR sources are disaggregated			DR limited	System perspective	
		FCR	FRR	RR	RES	COM	IND	H&C	DHW	EV		OPER	INV
[4]	Yes	No	Yes	No	Yes	No	No	No	No	Yes	No	No	
[5]	Yes		~		Yes	No	No	No	No	Yes	No	No	
[27]	Yes		~			~			~		No	Yes	No
[28]	Yes	Yes	Yes	No	No	No	Yes		~		No	Yes	No
[29]	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	No
[30]	No		~		Yes	No	No	No	Yes	No	No	Yes	No
[31]	Yes	No	Yes	No	No	Yes	No		~		No	No	
[32]	Yes		~		Yes	Yes	Yes	Yes	Yes	No	Yes	No	
[33]	Yes	Yes	Yes	No		~			~		No	Yes	No
[34]	Yes	Yes	Yes	Yes		~			~		No	No	
[35]	No		~			~			~		No	Yes	No
[36]	Yes	No	Yes	No	Yes	No	No	Yes	No	Yes	Yes	No	
[37]	Yes	No	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No	
[38]	Yes		~			~			~		No	No	
[39]	Yes		~			~			~		No	No	
[40]	Yes		~		Yes	Yes	Yes		~		Yes	No	
[41]	No		~			~			~		Yes	No	
[42]	No	Yes	No	No	Yes	No	No	Yes	Yes	No	Yes	No	
[43]	No		~		Yes	No	No	No	Yes	No	Yes	No	
This Paper	**Yes**	**No**	**Yes**	**No**	**Yes**	**Yes**	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

~ Not specified.

demand resources. The model considers a time scale of hours for only four representative weeks of a year. Additionally, electricity generation is classified by technology and electricity demand by sector (residential, services and industrial). The residential and services sectors are also disaggregated in different consumption categories (H&C, DHW, EV, lighting and others), where H&C, DHW and EV are considered as potential flexible resources.

The contribution of this paper is to include the different demand assets in the reserves market formulation and their limitations. The mathematical formulation of the reserves could be stochastic or deterministic. The necessary input data for both formulations are the same; consequently, the only thing that changes is the equations determined. In the stochastic approach [29,32,36,37,48], variables and parameters would have been reused for the new model adding only an additional set to iterate and solve each equation for wholesale and upward and downward reserve markets. For this case, the deterministic approach has been modelled by including additional variables and parameters to consider the increase and decrease in generation or demand due to the secondary regulation market. With this procedure, the previous wholesale market is affected by the reserves market solution with the status of the storage technologies [38,49,50].

Fig. 1 briefly depicts the new formulation needed to model the reserves market, it distinguishes between modified constraints for energy suppliers and additional constraints. Fig. 2 summarizes the required input data, identifying also the additional data needs from this paper work, and the resulting outputs obtained from running the model.

2.1. Sets, parameters, and variables

The inclusion of the reserves market in the model affects the entire model formulation. Moreover, the particular equations affected are detailed below using the same format of symbols as in previous publications to facilitate comparison. Table 2 presents the sets, parameters, and variables used to model the reserves market. Note that all parameters are written in capital letters while variables are defined in lower case letters.

2.2. Objective function

The objective function was updated to take into account the additional energy produced by the generators that participate in the reserves market. The objective function of the model is to minimize total system costs and is presented in equation (1). Equations (2) to (4) calculate the corresponding installation, maintenance, and operating costs that comprise the objective function. The operation costs now include those that correspond to reserves market costs, as well as wholesale market costs. This might alter reality, like in real life, since the energy used to supply reserves needs is not known in advance and hence, optimized.

$$costs = installcosts + fixcosts + operationcosts \tag{1}$$

$$\begin{aligned} installcosts = \sum_i (&COSTDER_{PV}*powerpv_i + COSTDER_{ES}*batcapacity_i \\ &+ COSTDER_{HP}*powerhp_i + COSTDER_{ERD}*powererd_i \\ &+ newinstall_i*COSTINSTALL_i) \end{aligned} \tag{2}$$

$$\begin{aligned} fixcosts = \sum_i &(COSTOMFIX_i*(INSTALLED_i + newinstall_i) \\ &+ (PVCAP_i + powerpv_i)*COSTOM_{PV} + (HPCAP_i + powerhp_i)*COSTOM_{HP} + (ESCAP_i + batcapacity_i)*COSTOM_{ES}) \end{aligned} \tag{3}$$

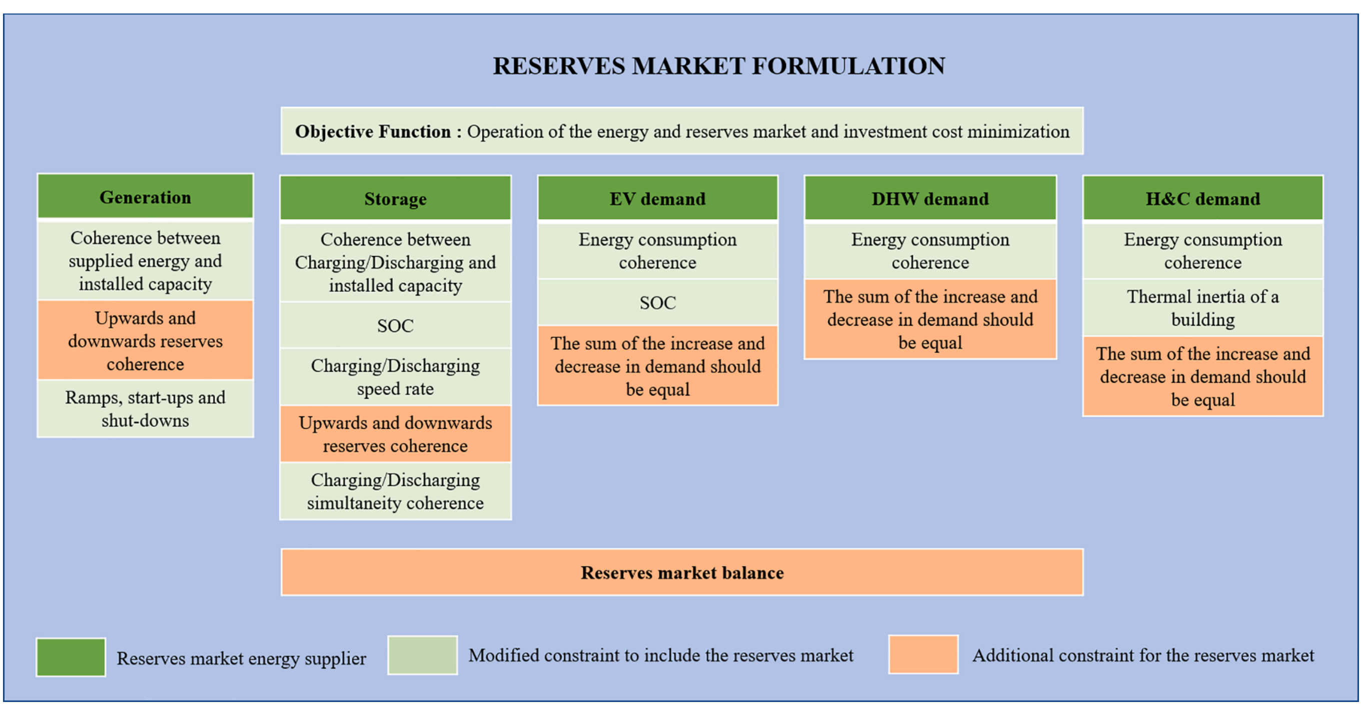

Fig. 1. Reserves market formulation organization.

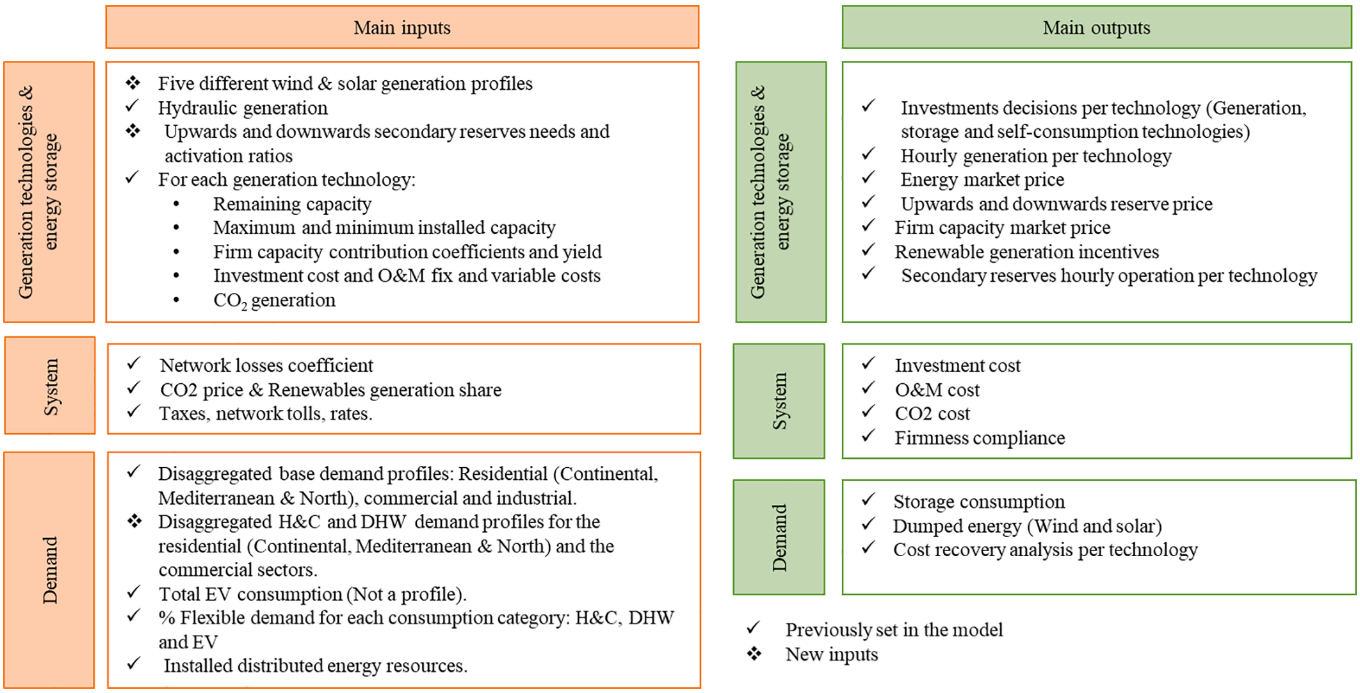

Fig. 2. Model inputs and outputs schematically.

$$\begin{aligned} operationcosts = & \sum_{w,d} MONTHDAYS_{w,d} \sum_{h} (COSTOMVAR_i + INDTAX_i) \\ & * (energysell_{i,w,d,h} + dumped_{i,w,d,h} + energysellupR_{i,w,d,h} \\ & - energyselldownR_{i,w,d,h}) + (energyproduced_{i,w,d,h} \\ & + energyproducedupR_{i,w,d,h} \\ & - energyproduceddownR_{i,w,d,h}) * CO2EMI_i * EMICOST \\ & + (startup_{i,w,d,h} + startupR_{i,w,d,h} + stop_{i,w,d,h} \\ & + stopR_{i,w,d,h}) * STARTUP_i \end{aligned} \tag{4}$$

2.3. Generation technologies able to provide reserves

The total energy produced for the wholesale and reserves markets from nonrenewable technologies, *inr*, is limited in equation (5). The total production at each hour should not exceed the total installed capacity. Besides, the coherence of the energy provided for the downward reserve is controlled with equation (6). The amount of power that nonrenewable technologies able to provide reserves and which include OCGT, CCGT, and hydroelectric technologies can produce for downward reserve capacity should be lower than their energy production for the wholesale market plus the upward reserves market at that same hour.

$$\begin{aligned} (INSTALLED_{inr} + newinstall_{inr}) \geq & energyproduced_{inr,w,d,h} \\ & + energyproducedupR_{inr,w,d,h} \\ & - energyproduceddownR_{inr,w,d,h} \forall inr, w, d, h \end{aligned} \tag{5}$$

$$\begin{aligned} & energyproduced_{inr,w,d,h} + energyproducedupR_{inr,w,d,h} \\ & \geq energyproduceddownR_{inr,w,d,h} \forall w, d, h \end{aligned} \tag{6}$$

Total hydroelectric energy production for the wholesale and reserves market cannot surpass the available water for this technology in one week due to equation (7). The sum of the wholesale and reserves market production from a CCGT source is limited in equation (8). It should be less than the available capacity for this technology at every hour.

$$\begin{aligned} & \sum_{d} ((INSTALLED_{hydro} + newinstall_{hydro}) * HYDROAVAILABLE_{w,d}) \\ & \geq \sum_{d,h} energyproduced_{hydro,w,d,h} + energyproducedupR_{hydro,w,d,h} \forall w \end{aligned} \tag{7}$$

$$\begin{aligned} & (INSTALLED_{CCGT} + newinstall_{CCGT}) * CAPDISP_{CCGT} \geq energyproduced_{CCGT,w,d,h} \\ & + energyproducedupR_{CCGT,w,d,h} - energyproducedDownR_{CCGT,w,d,h} \forall w, d, h \end{aligned} \tag{8}$$

2.4. Ramps, start-ups and shutdowns

The thermal technologies that compose the *ither* set, have their energy production limited with the number of active power plants and their maximum size (9). Minimum production must also comply with the technical minimum of the plants. This compliance is restricted by constraint (10).

$$\begin{aligned} nplants_{ither,w,d,h} * PRODMAX_{ither} \geq & energyproduced_{ither,w,d,h} \\ & + energyproducedupR_{ither,w,d,h} \forall ither, w, d, h \end{aligned} \tag{9}$$

$$\begin{aligned} & energyproduced_{ither,w,d,h} - energyproducedDownR_{ither,w,d,h} \\ & \geq nplants_{ither,w,d,h} * PRODMIN_{ither} \forall ither, w, d, h \end{aligned} \tag{10}$$

Moreover, the number of new active power plants for thermal technologies at each hour is estimated by equations (11) and (12) with the start-ups and shutdowns performed.

$$\begin{aligned} nplants_{ither,w,d,h} - nplants_{ither,w,d,h-1} = & startup_{ither,w,d,h} - stop_{ither,w,d,h} \\ & + startupR_{ither,w,d,h} - stopR_{ither,w,d,h} \forall ither, w, d, h \geq 2 \end{aligned} \tag{11}$$

$$\begin{aligned} nplants_{ither,w,d,h} - nplants_{ither,w,d-1,24} = & startup_{ither,w,d,h} - stop_{ither,w,d,h} \\ & + startupR_{ither,w,d,h} - stopR_{ither,w,d,h} \forall ither, w, d \geq 2, h = 1 \end{aligned} \tag{12}$$

Equations (13) and (14) guarantee that thermal technologies' up and down ramping limits are not surpassed.

Table 2
Sets, parameters and variables defined for SPLODER.

Sets	
i	Technology type {Nuclear, CCGT,OCGT, Coal, Cogeneration, Pumping Storage, Batteries, Solar, Wind, Solar Thermal, Hydroelectric, Flowing, Biopower, Thermal renewable, Demand}
ires ∈ *i*	Technologies able to provide reserves {CCGT, Hydroelectric, Storage}
ist ∈ *i*	Storage technologies {Pumping Storage and Batteries}
ict ∈ *i*	Consumption categories without industry {Continental, Mediterranean, North and Commercial}
icres ∈ *i*	Residential consumption categories {Continental, Mediterranean and North}
iccom ∈ *i*	Commercial consumption category {Commercial}
ither ∈ *i*	Thermal technologies {Nuclear, CCGT,OCGT and Coal}
inr ∈ *i*	Nonrenewable technologies {Nuclear, CCGT,OCGT, Coal, Cogeneration, Hydroelectric, Flowing, Biopower}
w	Week {1–4}
d	Day of the week {1–7}
h	Hour {1–24}
Parameters	
$ACTRD_{w,d,h}$	Activated downwards reserves ratio over capacity requirement [%]
$ACTRU_{w,d,h}$	Activated upwards reserves ratio over capacity requirement [%]
$ASIGDR_{w,d,h}$	Downwards reserve requirement ratio over total demand [%]
$ASIGUR_{w,d,h}$	Upwards reserve requirement ratio over total demand [%]
BOILEREFF	Boiler efficiency ratio is 0.8 [%]
$CAPDISP_i$	Availability ration for nuclear, CCGT, Coal & OCGT technologies [%]
$CHARHOURS_i$	Charging hours for each type of storage [h]
CHARMAXEV	Maximum SOC capacity for each EV [MWh]
C_i	Thermal building wall equivalent capacitor [kWh/°C]
$CO2EMI_i$	Tons of CO_2 emitted for each MWh generated with each technology [tonCO_2/MWh]
$COPAC_i$	Coefficient of Performance [-]
$COSTDER_i$	Distributed energy sources installation cost [€/kW]
$COSTINSTALL_i$	Installation cost [€/MW]
$COSTOMFIX_i$	Operation and maintenance fix costs [€/MW]
$COSTOM_i$	Maintenance DER Cost [€/kW/year]
$COSTOMVAR_i$	Operation and maintenance variable costs [€/MWh]
$DEMANDTHER_{i,w,d,h}$	DHW demand profiles [MWh]
$DISCHARHOURS_i$	Discharging hours for each type of storage [h]
$DNI_{i,w,d,h}$	Solar Direct Normal Irradiance for the different zones [W/m^2]
$DRDHW_{i,w,d,h}$	Percentage of DR stablished for DHW demand [%]
EFFCHAREV	EV charging efficiency [%]
EMICOST	Cost per ton of CO2 [€/MtonCO_2]
$ERDCAP_i$	ERD Power already installed for each agent [MW]
$ESCAP_i$	ES Power already installed for each agent [MW]
EVAVAIDEM	Hourly indicator (0 or 1) to gather when flexible EV are available to change their demand [-]
$EVBASEDEM_{i,w,d,h}$	Hourly demand from fix EV [MW]
$EVCAP24_i$	EV capacity available from the 24 h smart vehicles [MW]
$EVCAP_i$	EV available capacity from the day or night smart vehicles [MW]
$EVTRAVEL_i$	Discharged power of an EV when is not recharging (full capacity is discharged in 10 h for residential vehicles and in 14 h for commercial) [MWh/h]
$HPCAP_i$	HP Power already installed for each agent [MW]
$HYDROAVAILABLE_{w,d}$	Available water for each day of the week for hydroelectric technology [h]
$INDTAX_i$	Specific taxes for each technology [€/MWh]
$INSTALLED_i$	Existing power previously installed for each technology i [MW]
LOSSESHP	Losses produced in the HP functioning [p.u.]
LOSSESPV	Losses produced in electronics and those due to the slope of the solar panel [p.u.]
M	Very large number: 100,000
$MONTHDAYS_{w,d}$	Number of days along the year that each representative day represent [days]

Table 2 (*continued*)

Sets	
$NUM_{i,w}$	People [n°]
$OUTTEMP_{i,w,d,h}$	Outdoor temperature profiles for each climate zone [°C]
$PRODMAX_i$	Typical size of a power plant for CCGT, OCGT and nuclear power [MW]
$PRODMIN_i$	Minimum size of a power plant for CCGT, OCGT and nuclear power [MW]
$PVCAP_i$	PV Power already installed for each agent [MW]
$RAMPDOWN_i$	Maximum downwards ramp for CCGT, OCGT and nuclear power [MW]
$RAMPUP_i$	Maximum upwards ramp for CCGT, OCGT and nuclear power [MW]
RUA_i	Resistance of the overall heat transfer coefficient [°C/kWh]
$STARTUP_i$	Cost of starting up a power plant [€/power plant]
TAU_i	Thermal inertia = RUA*C [-]
$WIND_{i,w,d,h}$	Wind Power profile for the different zones[p.u.]
$YIELD_{ist}$	Storage technologies yield [%]
Binary Variables (0 or 1)	
$binstoem_{i,w,d,h}$	Indicates whether the storage technology is discharging or not for the wholesale market
$binstorr_{i,w,d,h}$	Indicate whether the storage technology is discharging or not for the reserves market
Positive Variables (>=0)	
$acinput_{i,w,d,h}$	Hourly consumption of one heat pump that is cooling [MWh]
$batcapacity_i$	New installed distributed batteries [MW]
$charge_{i,w,m,h}$	Storage charge at each hour [MW]
costs	Total system costs [€]
$discharge_{i,w,m,h}$	Storage discharge at each hour [MW]
$dumped_{i,w,d,h}$	Energy dumped [MWh]
$energybought_{i,w,d,h}$	Hourly energy bought by each technology *i* [MWh]
$energyproduceddownR_{i,w,d,h}$	Hourly energy produced by each technology i for downward reserves [MWh]
$energyproduced_{i,w,d,h}$	Hourly energy produced by each technology *i* [MWh]
$energyproducedupR_{i,w,d,h}$	Hourly energy produced by each technology i for upwards reserves [MWh]
$energyselldownR_{i,w,d,h}$	Hourly energy sold by each technology i for downward reserves [MWh]
$energysell_{i,w,d,h}$	Hourly energy sold by each technology *i* [MWh]
$energysellupR_{i,w,d,h}$	Hourly energy sold by each technology i for upward reserves [MWh]
$erd_{i,w,d,h}$	Electric radiator consumption for each device [kWh]
$evcharge24_{i,w,d,h}$	EV Charging for vehicles considered smart all along the day (24 h) [MWh]
$evcharge_{i,w,d,h}$	EV Charging for smart vehicles during the day or at night [MWh]
$evsoc_{i,w,d,h}$	State of charge of the EV [MWh]
fixcosts	Maintenance costs [€]
$hptemp_{i,w,d,h}$	Hourly consumption of one heat pump that is heating [MWh]
$incac_{i,w,d,h}$ $decac_{i,w,d,h}$	Hourly increase and decrease in cooling consumption to supply reserves [MWh]
$incerd_{i,w,d,h}$ $decerd_{i,w,d,h}$	Hourly increase and decrease in DHW consumption to supply reserves [MWh]
$incev_{i,w,d,h}$ $decev_{i,w,d,h}$	Hourly increase and decrease in charging electric vehicles to supply reserves [MWh]
$inchpt_{i,w,d,h}$ $dechpt_{i,w,d,h}$	Hourly increase and decrease in heating consumption to supply reserves [MWh]
installcosts	Costs related with installation [€]
$neg_{i,w,d,h}$	Negative production change [MW]
$newinstall_i$	New installed capacity for each technology *i* [MW]
$nplants_{i,w,d,h}$	Number of activated plants for thermal technologies [n°]
operationcosts	Operation costs of generators including start-up and CO_2 emissions costs [€]
$pos_{i,w,d,h}$	Positive production change [MW]
$powererd_i$	New installed Electric Radiators [MW]
$powerhp_i$	New installed Heat Pumps [MW]
$powerpv_i$	New installed PV distributed panels [MW]
$schar_{i,w,d,h}$	Stop charging for storage (Batteries and pumping) [MWh]
$sdischar_{i,w,d,h}$	Stop discharging for storage (Batteries and pumping) [MWh]
$start\text{-}up_{,i,w,d,h}$ $startupR_{,i,w,d,h}$	Start-up of a power plant in response to wholesale or reserve needs [n° power plants]

(*continued on next page*)

Table 2 (*continued*)

Sets	
stop $_{i,\ w,\ d,\ h}$ *stopR* $_{i,\ w,\ d,\ h}$	Stop a power plant in response to wholesale or reserve needs [n° power plants]
$tempin_{i,w,d,h}$	Indoor temperature profiles for a building [°C]
$xchar_{i,\ w,\ d,\ h}$	Extra charge for storage (Batteries and pumping) [MWh]
$xdischar_{i,\ w,\ d,\ h}$	Extra discharge for storage (Batteries and pumping) [MWh]

$$nplants_{ither,w,d,h}{}^{*}RAMPUP_{ither} \geq pos_{ither,w,d,h} - PRODMAX_{ither}{}^{*}(startup_{ither,w,d,h} + startupR_{ither,w,d,h})\forall ither, w, d \geq 2, h \geq 2 \tag{13}$$

$$nplants_{ither,w,d,h}{}^{*}RAMPDOWN_{ither} \geq neg_{ither,w,d,h} - PRODMIN_{ither}{}^{*}(stop_{ither,w,d,h} + stopR_{ither,w,d,h})\forall ither, w, d \geq 2, h \geq 2 \tag{14}$$

The positive, *pos*, or negative, *neg*, power change is defined at each hour for nonrenewable technologies by equations (15) and (16), including reserves market participation for hydroelectric and CCGT technologies.

$$pos_{inr,w,d,h} - neg_{inr,w,d,h} = energyproduced_{inr,w,d,h} - energyproduced_{inr,w,d,h-1} + energyproducedupR_{inr,w,d,h} - energyproducedupR_{inr,w,d,h-1} - energyproduceddownR_{inr,w,d,h} + energyproduceddownR_{inr,w,d,h-1} \quad \forall inr, w, d, h \geq 2 \tag{15}$$

$$pos_{inr,w,d,h} - neg_{inr,w,d,h} = energyproduced_{inr,w,d,h} - energyproduced_{inr,w,d-1,24} + energyproducedupR_{inr,w,d,h} - energyproducedupR_{inr,w,d-1,24} - energyproducedDownR_{inr,w,d,h} + energyproduceddownR_{inr,w,d-1,24} \quad \forall inr, w, d \geq 2, h = 1 \tag{16}$$

2.5. Storage technologies able to provide reserves

Four new variables were introduced to represent the contribution of storage in reserves. When batteries are charging, it can increase their consumption, *xchar*, or reduce it, *schar*. Conversely, when batteries are discharging, they can produce more, *xdischar*, or produce less, *sdischar*. Constraints (17) to (21) control that the total storage capacity according to the installed capacity is not exceeded, even with the additional charging and stop charging performed for the reserves market.

$$(INSTALLED_{ist} + newinstall_{ist}){}^{*}DISCHARHOURS_{ist} \geq soc_{ist,p,w,d,h} \tag{17}$$

$$(INSTALLED_{ist} + newinstall_{ist}){}^{*}DISCHARHOURS_{ist} \geq soc_{ist,p,w,d,h-1} + (charge_{ist,w,d,h} + xchar_{ist,w,d,h} - schar_{ist,w,d,h}){}^{*}YIELD_{ist}\forall \mathrm{ist, w, d, h} > 1 \tag{18}$$

$$(INSTALLED_{ist} + newinstall_{ist}){}^{*}DISCHARHOURS_{ist} \geq soc_{ist,p,w,d-1,24} + (charge_{ist,w,d,h} + xchar_{ist,w,d,h} - schar_{ist,w,d,h}){}^{*}YIELD_{ist}\forall \mathrm{ist, w, d} >, \mathrm{h} = 1 \tag{19}$$

$$(INSTALLED_{ist} + newinstall_{ist}){}^{*}DISCHARHOURS_{ist} \geq soc_{ist,p,w-1,7,24} + (charge_{ist,w,d,h} + xchar_{ist,w,d,h} - schar_{ist,w,d,h}){}^{*}YIELD_{ist}\forall \mathrm{ist, w} > 1, \mathrm{d} = 1, \mathrm{h} = 1 \tag{20}$$

$$(INSTALLED_{ist} + newinstall_{ist}){}^{*}DISCHARHOURS_{ist} \geq soc_{ist,p,4,7,24} + (charge_{ist,w,d,h} + xchar_{ist,w,d,h} - schar_{ist,w,d,h}){}^{*}YIELD_{ist}\forall \mathrm{ist, w} = 1, \mathrm{d} = 1, \mathrm{h} = 1 \tag{21}$$

Constraints (22) to (25)calculate each storage type's state of charge (SOC) at every hour. The SOC at each hour equals the SOC at the previous hour, plus the charged energy for the reserves market minus the discharged energy for the wholesale and reserves market. The four equations only differ regarding the previous hour's SOC in which, due to the temporal granularity of the model, the sets to be referred to slightly change over time (depending on the week, the day, and the hour).

$$soc_{ist,w,d,h} = soc_{ist,w,d,h-1} + \left((charge_{ist,w,d,h} + xchar_{ist,w,d,h} - schar_{ist,w,d,h}){}^{*}YIELD_{ist}\right) - discharge_{i,w,d,h} - xdischar_{ist,w,d,h} + sdischar_{ist,w,d,h}\forall ist, w, d, \mathrm{h} > 1 \tag{22}$$

$$soc_{ist,w,d,h} = soc_{ist,w,d-1,24} + \left((charge_{ist,w,d,h} + xchar_{ist,w,d,h} - schar_{ist,w,d,h}){}^{*}YIELD_{ist}\right) - discharge_{i,w,d,h} - xdischar_{ist,w,d,h} + sdischar_{ist,w,d,h}\forall ist, w, d > 1, \mathrm{h} = 1 \tag{23}$$

$$soc_{ist,w,d,h} = soc_{ist,w-1,7,24} + \left((charge_{ist,w,d,h} + xchar_{ist,w,d,h} - schar_{ist,w,d,h}){}^{*}YIELD_{ist}\right) - discharge_{i,w,d,h} - xdischar_{ist,w,d,h} + sdischar_{ist,w,d,h}\forall ist, w > 1, d = 1, \mathrm{h} = 1 \tag{24}$$

$$soc_{ist,w,d,h} = soc_{ist,4,7,24} + \left((charge_{ist,w,d,h} + xchar_{ist,w,d,h} - schar_{ist,w,d,h}){}^{*}YIELD_{ist}\right) - discharge_{i,w,d,h} - xdischar_{ist,w,d,h} + sdischar_{ist,w,d,h} \quad \forall ist, w = 1, d = 1, \mathrm{h} = 1 \tag{25}$$

Constraints (26) to (29) are the boundary conditions for the maximum energy that can be discharged at each time of the year, considering the reserves market. The $YIELD_{ist}$ considered in the model contains the round-trip efficiency. Hence, it is not necessary to multiply the $discharge_{i,p,w,m,h}$ variable again.

$$soc_{ist,w,d,h-1} \geq discharge_{i,w,d,h} + xdischar_{ist,w,d,h} - sdischar_{ist,w,d,h}\forall ist, w, d, \mathrm{h} > 1 \tag{26}$$

$$soc_{ist,p,w,d-1,24} \geq discharge_{i,w,d,h} + xdischar_{ist,w,d,h} - sdischar_{ist,w,d,h}\forall ist, w, d > 1, \mathrm{h} = 1 \tag{27}$$

$$soc_{ist,w-1,7,24} \geq discharge_{i,w,d,h} + xdischar_{ist,w,d,h} - sdischar_{ist,w,d,h}\forall ist, w > 1, d = 1, \mathrm{h} = 1 \tag{28}$$

$$soc_{ist,4,7,24} \geq discharge_{i,w,d,h} + xdischar_{ist,w,d,h} - sdischar_{ist,w,d,h}\forall ist, w = 1, d = 1, \mathrm{h} = 1 \tag{29}$$

Constraints (30) and (31)set the charging and discharging speed rate depending on the capacity of the storage hours. Constraint (32) guarantees that the discharged water from the pumping vessel has been refilled throughout the week, considering both, the wholesale and the reserves markets.

$$(INSTALLED_{ist}+newinstall_{ist})^{*}\frac{DISCHARHOURS_{ist}}{CHARHOURS_{ist}} \geq charge_{ist,w,m,h}+xchar_{ist,w,m,h} \forall ist,w,m,h \quad (30)$$

$$(INSTALLED_{ist}+newinstall_{ist})^{*}\frac{DISCHARHOURS_{ist}}{CHARHOURS_{ist}} \geq discharge_{ist,w,m,h}+xdischar_{ist,w,m,h} \forall ist,w,m,h \quad (31)$$

$$\sum_{w,d} MONTHDAYS_{w,d}{}^{*}\sum_{h}(energysell_{i,w,d,h}+xdischar_{i,w,d,h}-sdischar_{i,w,d,h}) = YIELD_{ist}{}^{*}\sum_{w,d} MONTHDAYS_{w,d}{}^{*}\sum_{h}(energybought_{i,w,d,h}+xchar_{i,w,d,h} - schar_{i,w,d,h}) \quad (32)$$

The total amount of energy provided for upward and downward reserves from storage technologies is defined with the extra charge and discharge variables (*xchar, xdischar*) and the stop charging or discharging variables (*schar, sdischar*). This sum of the energy supplied by storage technologies is presented in equations (33) and (34). Besides, the amount of energy that stops charging or discharging should be less than the corresponding energy that was being charged or discharged at that time. This is limited in constraints (35) and (36).

$$energysellupR_{ist,w,d,h} = xdischar_{ist,w,d,h}+schar_{ist,w,d,h} \forall ist,w,d,h \quad (33)$$

$$energysellDownR_{ist,w,d,h} = xchar_{ist,w,d,h}+sdischar_{ist,w,d,h} \forall ist,w,d,h \quad (34)$$

$$charge_{ist,w,d,h} \geq schar_{ist,w,d,h} \forall ist,w,d,h \quad (35)$$

$$discharge_{ist,w,d,h} \geq sdischar_{ist,w,d,h} \forall ist,w,d,h \quad (36)$$

One restriction of the model is that when a storage type is charging, it cannot be discharged at the same time, neither for the wholesale market (constraints (37)(38)) nor the reserves market (constraints (39)-(42)).

$$binstoem_{ist,w,d,h}{}^{*}M \geq discharge_{ist,w,m,h} \quad (37)$$

$$(1-binstoem_{ist,w,d,h})^{*}M \geq charge_{ist,w,m,h} \quad (38)$$

$$binstorr_{ist,w,d,h}{}^{*}M \geq xdischar_{ist,w,d,h} \forall ist,w,d,h \quad (39)$$

$$(1-binstorr_{ist,w,d,h})^{*}M \geq xchar_{ist,w,d,h} \forall ist,w,d,h \quad (40)$$

$$binstorr_{ist,w,d,h}{}^{*}M \geq energysellupR_{ist,w,d,h} \forall ist,w,d,h \quad (41)$$

$$(1-binstorr_{ist,w,d,h})^{*}M \geq energyselldownR_{ist,w,d,h} \forall ist,w,d,h \quad (42)$$

2.6. EV demand

EV demand is assumed to be partially flexible. SPLODER EV types differentiate between EVs with fixed demand that follow a base consumption profile that is the same all day (BASE EVs), and smart charging vehicles, for which the model distinguishes three different categories:

- SMART DAY: smart vehicles that are charged during the day (from 9 a.m. to 7p.m.) and are assigned to commercial sector consumption. They are discharged uniformly during the 14 h of the day when they are disconnected
- SMART NIGHT: EVs that can be charged at any time during the night period (from 7p.m. to 9 a.m.) and are assigned to residential sector consumption. They are discharged uniformly during the 10 h disconnected.
- SMART 24 h: smart EVs that can be charged at any time during the 24 h of a day. They are assumed to be discharged for 10 consecutive hours in a day.

Intelligent EVs, SMART DAY and SMART NIGHT types do not have unlimited available capacity for charging. Therefore, constraints (43) and (44) limit their capacity, also considering the upwards reserve provided. Two new variables have been added per flexible demand type. The variable *incX* represents an increase in consumption, whereas the variable *decX* means a decrease in consumption. The *decev* variable represents the energy supplied from EVs for upwards reserve, which means stopping the charging that was initially scheduled. Constraint (45) guarantees that the total initially charged power is higher than the amount of upwards reserve provided.

$$EVCAP_{ict} \geq evsoc_{ict,w,d,h-1}+(evcharge_{ict,w,d,h} + incev_{ict,w,d,h})^{*}EFFCHAREV \forall ict,w,d,h>1 \quad (43)$$

$$EVCAP_{ict} \geq evsoc_{ict,w,d-1,24}+(evcharge_{ict,w,d,h} + incev_{ict,w,d,h})^{*}EFFCHAREV \forall ict,w,d,h=1 \quad (44)$$

$$evcharge_{ict,w,d,h}+incev_{ict,w,d,h} \geq decev_{ict,w,d,h} \forall ict,w,d,h \quad (45)$$

Constraints (46), (47) and (48) define the state of charge of the EVs, considering increase and decrease in consumption due to demand participation in wholesale and reserves markets.

$$evsoc_{ict,w,d,h} = evsoc_{ict,w,d,h-1}+(evcharge_{ict,w,d,h}+incev_{ict,w,d,h} - decev_{ict,w,d,h})^{*}EFFCHAREV - EVTRAVEL_{icres}{}^{*}EVCAP_{ict}{}^{*} (1-EVAVAIDEM_{icres,w,d,h}) - EVTRAVEL_{iccom}{}^{*}EVCAP_{ict}{}^{*} (1-EVAVAIDEM_{iccom,w,d,h}) \forall ict,w,d,h \geq 2 \quad (46)$$

$$evsoc_{ict,w,d,h} = evsoc_{ict,w,d-1,24}+(evcharge_{ict,w,d,h}+incev_{ict,w,d,h} - decev_{ict,w,d,h})^{*}EFFCHAREV - EVTRAVEL_{icres}{}^{*}EVCAP_{ict}{}^{*} (1-EVAVAIDEM_{icres,w,d,h}) - EVTRAVEL_{iccom}{}^{*}EVCAP_{ict}{}^{*} (1-EVAVAIDEM_{iccom,w,d,h}) \forall ict,w,d \geq 2,h=1 \quad (47)$$

$$evsoc_{ict,w,d,h} = evsoc_{ict,w,1,0}+(evcharge_{ict,w,d,h}+incev_{ict,w,d,h} - decev_{ict,w,d,h})^{*}EFFCHAREV - EVTRAVEL_{icres}{}^{*}EVCAP_{ict}{}^{*} (1-EVAVAIDEM_{icres,w,d,h}) - EVTRAVEL_{iccom}{}^{*}EVCAP_{ict}{}^{*} (1-EVAVAIDEM_{iccom,w,d,h}) \forall ict,w,d=1,h=1 \quad (48)$$

Intelligent EVs, have their maximum charging capacity limited by constraint (49) for the SMART DAY and NIGHT vehicles and by constraint (50) for the SMART 24 h vehicles. Moreover, constraint (51) forces the SMART 24 h vehicles to charge the discharged power throughout the 14 h of the day they are considered to be connected to a recharging point.

$$EVCAP_{ict}{}^{*}CHARMAXEV^{*}EVAVAIDEM_{ict,w,d,h} \geq evcharge_{ict,w,d,h}+incev_{ict,w,d,h} \forall ict,w,d,h \quad (49)$$

$$EVCAP24_{ict}{}^{*}CHARMAXEV \geq evcharge24_{ict,w,d,h}+incev_{ict,w,d,h} \forall ict,w,d,h \quad (50)$$

$$\sum_{h}(evcharge24_{ict,w,d,h}+incev_{ict,w,d,h}-decev_{ict,w,d,h})^{*}EFFCHAREV = EVTRAVEL_{icres}{}^{*}EVCAP24_{ict} \forall ict,w,d \quad (51)$$

2.7. Domestic hot water Demand

To provide DHW, electric radiators (ERD) are the installed devices used to represent immersion heaters. Constraint (52) limits ERD consumption to total installed capacity. The coherence of the energy provided for the upwards reserve is controlled by constraint (53). Providing upward reserve from the demand side means stopping consumption. Therefore, this amount should be lower than the total expected consumption of that consumption category from the wholesale market, plus the increase in consumption planned to provide downward reserve. On the one hand, the total DHW consumption profile should be consumed, although the hour when it is consumed can change for the flexible part. Constraint (54), guarantees that the entire consumption profile is consumed at some point. On the other hand, the fixed DHW demand cannot be shifted. This condition is met by equation (55).

Table 3
Geographical distribution of solar and wind generation profiles.

ZONE	Solar Spain provinces	Wind Spain provinces
A1	Galicia & Asturias	Galicia, Asturias, Cantabria & Castilla Leon
A2	Valencia & Murcia	Pais vasco, Navarra, Aragón & La Rioja
A3	Aragón, Cataluña, Extremadura, Madrid, Castilla La Mancha, & Andalucia	Cataluña, Valencia & Murcia
A4	Castilla Leon	Andalucia
A5	Cantabria,Pais vasco, Navarra & La Rioja	Extremadura, Madrid & Castilla La Mancha

$$powerhp_{ict} + HPCAP_{ict} \geq NUM_{ict,w} * \left(hptemp_{ict,w,d,h} + inchpt_{ict,w,d,h}\right) + NUM_{ict,w} * \left(acinput_{ict,w,d,h} + incac_{ict,w,d,h}\right) \forall ict, w, d, h \tag{56}$$

$$tempin_{ict,w,d,h} = tempin_{ict,w,d,h-1} + \left(tempin_{ict,w,d,h-1} - OUTTEMP_{ict,w,d,h-1}\right) * \frac{2}{TAU_{ict}} + (hptemp_{ict,w,d,h} + inchpt_{ict,w,d,h} - dechpt_{ict,w,d,h}) * COPAC_{ict} * (1 - LOSSESHP) + GAStemp_{ict,w,d,h} * BOILEREFF - (acinput_{ict,w,d,h} + incac_{ict,w,d,h} - decac_{ict,w,d,h}) * COPAC_{ict} * (\frac{RUA_{ict}}{2} - \frac{2}{C_{ict}}) - ((hptemp_{ict,w,d,h-1} + inchpt_{ict,w,d,h-1} - dechpt_{ict,w,d,h-1}) * COP_{ict} * (1 - LOSSESHP - (acinput_{ict,w,d,h-1} + incac_{ict,w,d,h-1} - decac_{ict,w,d,h-1}) * COPAC_{ict} * (\frac{RUA_{ict}}{2} - \frac{2}{C_{ict}})) \forall ict, w, d, \mathrm{h} > 1 \tag{57}$$

$$tempin_{ict,w,d,h} = tempin_{ict,w,d-1,24} + \left(tempin_{ict,w,d-1,24} - OUTTEMP_{ict,w,d-1,24}\right) * \frac{2}{TAU_{ict}} + (hptemp_{ict,w,d,h} + inchpt_{ict,w,d,h} - dechpt_{ict,w,d,h}) * COPAC_{ict} * (1 - LOSSESHP) + GAStemp_{ict,w,d,h} * BOILEREFF - (acinput_{ict,w,d,h} + incac_{ict,w,d,h} - decac_{ict,w,d,h}) * COPAC_{ict} * (\frac{RUA_{ict}}{2} - \frac{2}{C_{ict}}) - ((hptemp_{ict,w,d-1,24} + inchpt_{ict,w,d-1,24} - dechpt_{ict,w,d-1,24}) * COPAC_{ict} * (1 - LOSSESHP) - (acinput_{ict,w,d-1,24} + incac_{ict,w,d-1,24} - decac_{ict,w,d-1,24}) * COPAC_{ict} * (\frac{RUA_{ict}}{2} - \frac{2}{C_{ict}})) \forall ict, w, d > 1, \mathrm{h} = 1 \tag{58}$$

$$powererd_{ict} + ERDCAP_{ict} \geq erd_{ict,w,d,h} + incerd_{ict,w,d,h} \forall ict, w, d, h \tag{52}$$

$$erd_{ict,w,d,h} + incerd_{ict,w,d,h} \geq decerd_{ict,w,d,h} \forall ict, w, d, h \tag{53}$$

$$\sum_h erd_{ict,w,d,h} + incerd_{ict,w,d,h} - decerd_{ict,w,d,h} = \sum_h DEMANDTHER_{ict,w,d,h} \forall ict, w, d \tag{54}$$

$$erd_{ict,w,d,h} - decerd_{ict,w,d,h} \geq DEMANDTHER_{ict,w,d,h} * (1 - DRDHW_{ict}) \forall ict, w, d, h \tag{55}$$

2.8. Heating and cooling Demand

For heating and cooling purposes, heat pumps (HP) are the available electric devices. The total amount of electric heating and cooling installed capacity should always be higher than the total consumption. This is limited in equation (56). The model's internal formulation of the heating and cooling needs considers outdoor temperatures and a comfort range for indoor temperatures considering the thermal inertia of a building. Equations (57) and (58) guarantee that the indoor temperature is within the established comfort range, even when there is an increase or decrease in flexible demand due to its reserve market participation.

A decrease in heating and cooling demand when providing reserves means to stop consuming. Therefore, this decrease should be lower the expected consumption at that particular time. This is limited by equations (59) and (60).

$$hptemp_{ict,w,d,h} + inchpt_{ict,w,d,h} \geq dechpt_{ict,w,d,h} \forall ict, w, d, h \tag{59}$$

$$ac + incac_{ict,w,d,h} \geq decac_{ict,w,d,h} \forall ict, w, d, h \tag{60}$$

2.9. Reserve market balance

The wholesale market balance equation is not affected by the reserves market needs to guarantee the balance of production and demand in this market. Therefore, equations (61) and (62) are added separately to collect the new balance equations for the upward and downward reserves market. The reserve needs have been estimated depending on the total *energySell* decided for each hour, considering the ratio of requirements needed and the activation ratio of this requirement as in [50].

$$\sum_i (energysellupR_{i,w,d,h} + decerd_{i,w,d,h} + NUM_{ict,w} * (dechpt_{i,w,d,h} + decac_{i,w,d,h}) + decev_{i,w,d,h}) = \sum_i energysell_{i,w,d,h} * ASIGUR_{w,d,h} * ACTRU_{w,d,h} \forall w, d, h \tag{61}$$

$$\sum_{i}(energyselldownR_{i,w,d,h}+incerd_{i,w,d,h}+NUM_{ict,w}*(inchpt_{i,w,d,h}+incac_{i,w,d,h})+incev_{i,w,d,h})=\sum_{i}energysell_{i,w,d,h}*ASIGDR_{w,d,h}*ACTRD_{w,d,h}\forall w,d,h \quad (62)$$

Two different variables that represent the energy produced by each generation technology to provide upward and downward reserves are required to be able to model the reserves market for storage technologies and their peculiarities. Equations (63) and (64) balance the two different variables. For all generation technologies from set "I" that are not included in the set "ires", both variables would acquire a null value.

$$energysellupR_{i,w,d,h} = energyproducedupR_{i,w,d,h} \quad (63)$$

$$energyselldownR_{i,w,d,h} = energyproduceddownR_{i,w,d,h} \quad (64)$$

2.10. Flexible demand participating in reserve limitations

Shifted demand to provide reserves should be scheduled for another hour on the same day to keep daily consumption constant. Constraints (65), (66), (67), and (68) ensure that this shifted consumption is moved to another hour of the day for all consumption categories.

$\sum_h incerd_{ict,w,d,h} = \sum_h decerd_{ict,w,d,h} \forall ict, w, d(65).$
$\sum_h inchpt_{ict,w,d,h} = \sum_h dechpt_{ict,w,d,h} \forall ict, w, d(66).$
$\sum_h incac_{ict,w,d,h} = \sum_h decac_{ict,w,d,h} \forall ict, w, d(67).$
$\sum_h incev_{ict,w,d,h} = \sum_h decev_{ict,w,d,h} \forall ict, w, d(68).$

3. Scenarios and case studies

The previously required input data has been reused from the study presented in [46] which had the same time horizon as this study, which is the year 2030. The data previously defined and also used for this study include:

- The firm capacity coefficients assumed for each technology
- The 2019 existing generation capacity is expected to still be available in 2030
- The investment costs and the fixed and variable maintenance costs for both conventional and renewable technologies
- The fuel prices, CO_2 emission costs, and taxes for pollutant technologies

The newly required and some updated input data when applied to the Spanish system include:

1) The inclusion of five wind and five solar generation areas to invest in, whose difference remains in their generation profile in accordance with different geographical areas. Table 3 presents the geographical representation within Spain of the five solar and wind generation areas.

These profiles have been gathered from [51]. Besides, in order to take a small network representation into account, the grid access and connection capacity allowance published by Red Eléctrica de España (REE) [52] have been considered as limits of the maximum installed capacity for each geographical zone and technology, as presented in Table 4.

DR can involve different sources and technologies, such as distributed solar PV generation and battery storage. The deployment effect of these two technologies have been thoroughly studied as flexible sources, with the aim of justifying the need for investment in distributed solar PV [53,54] and for distributed batteries [55], although batteries are still not competitive. In this study, distributed solar PV generation capacity is previously installed, as an investment option its high cost makes it an undesirable choice, and distributed batteries are modelled, although neither are considered when referring to flexible demand analysis, as done in [56]. Therefore, the PV distributed investment is forced according to the roadmap [57] for each geographical zone. Solar technologies broken down into geographical zones refer to centralized PV, which has better efficiency than distributed PV. Therefore, the initial capacity was multiplied by a reduction factor to force the installation of a "Centralized capacity equivalent to the real distributed capacity" per zone. This reduction factor was obtained from [58], and the results are presented in Table 5.

Table 4
Maximum installed capacity in each solar and wind area.

Technology	Max Install [MW]
WIND1	15,469
WIND2	6,984
WIND3	5,123
WIND4	2,199
WIND5	1,746
SOLAR1	247
SOLAR2	14,576
SOLAR3	69,661
SOLAR4	14,273
SOLAR5	2,526

Table 5
Distributed solar generation installed capacity.

Zone	Distributed installed capacity [MW]	Distributed/ Centralized Ratio	Equivalent centralized capacity [MW]
A1	182	0.90	163
A2	1412	0.79	1110
A3	5940	0.76	4539
A4	339	0.76	258
A5	339	0.77	261

Table 6
Energy consumption and average traveled distance per type of vehicle.

Type of vehicle	Percentage of total EVs [%]	Energy consumption [KWh/100 km]	Distance [km/year]
Cars	71 %	20	15,000
Vans and buses	10 %	26	18,000
Motorcycles	19 %	6	12,000

Table 7
Amount of EVs for each EV category considered with the SPLODER model.

SPLODER EVs TYPES	Number of EVs	Percentage [%]
BASE	2,065,863	41 %
SMART NIGHT	1,910,170	38 %
SMART DAY	491,211	10 %
SMART 24 h	606,241	12 %
TOTAL	5,073,484	100 %

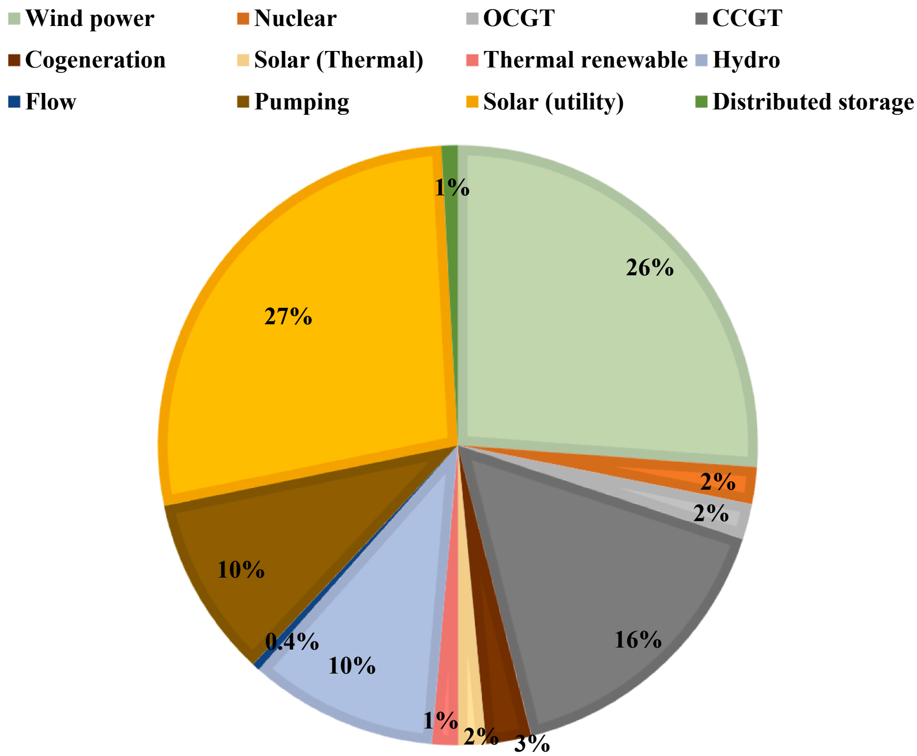

Fig. 3. Fixed installed electricity generation technology mix.

2) Disaggregated demand profiles, for the residential and services sector, into different consumption categories (DHW, H&C, lighting and others). These sensitive data can be found in [51]. The demand profiles are considered to be at the power plant busbars, so the losses in the network are zero, where, the energy generated (290TWh) = energy consumed (290TWh).
3) EV consumption data has also changed from previous studies. However, its formulation remains the same. The number of EVs was estimated considering different reports with the expected fleet growth through 2030 [59]. The consumption per vehicle [KWh/km] was adjusted according to data from [60] and [61], distinguishing between cars, motorcycles, and vans. The annual average distance driven by each type of vehicle was gathered from [62] data, all presented in Table 6.

The type of vehicle classification among the model options was calculated by using detailed information on the charging points, including their location and whether they are for private or public use [51]. The final input data for SPLODER is presented in Table 7.

4) Secondary reserves need and activation ratios. In this case, the publicly available information in [26] has been used to create a 5 year averages, from June 1, 2017 to May 31, 2022, of secondary reserve needs and activation, for upwards ($ASIGUR_{w,d,h}$ and $ACTRU_{w,d,h}$) and downwards reserve ($ASIGDR_{w,d,h}$ and $ACTRD_{w,d,h}$). The reserve needs ratio was calculated according to demand on an hourly basis, and the activation ratio was set according to reserve requirements. These average profiles have been suitably adapted to the time granularity of the model. Thus, the resulting hourly amount of reserve needed and activated in each scenario depends on the input demand profiles.

Table 8
Scenarios for the fixed and freely installed electricity generation technology mix.

Case Name	Reserves consideration	Amount of Flexible demand	Demand participation in reserves
20DR	No	20 %	No
RR_20DR	Yes	20 %	No
RR_0DR_dem	Yes	0 %	Yes
RR_20DR_dem	Yes	20 %	Yes
RR_40DR_dem	Yes	40 %	Yes
RR_60DR_dem	Yes	60 %	Yes

Table 9
Flexible energy available for each percentage of DR.

FLEXIBLE ENERGY [GWh]	0DR	20DR	40DR	60DR
H&C	0	13,589	27,177	40,766
DHW	0	8,067	16,134	24,201
EV	0	8,160	8,160	8,160

All scenarios have been studied under two different case studies for the installed electricity generation technology mix. First under an optimized technology mix (free installation is permitted) and subsequently under a fixed installed technology mix (no installation is allowed). The fixed installed electricity generation technology mix considered corresponds with the optimized installation of the most restrictive scenario from the freely installed case, which is the RR_0DR_dem scenario. The fixed installed electricity generation technology mix considered to perform under these conditions is presented in Fig. 3. This technology mix includes the solar and wind installed capacity committed to 2030 in the Spanish NECP[59]. With this condition, it is easier to draw conclusions about operating results and compare one scenario to another, as technology investment decisions do not distort results.

The scenarios considered address the role of DR providing reserves and its impact on electricity system costs and generation and storage investment planning. First, the comparison of two scenarios that have the same amount of flexible demand, with and without reserves market consideration, would give the value of considering reserves when

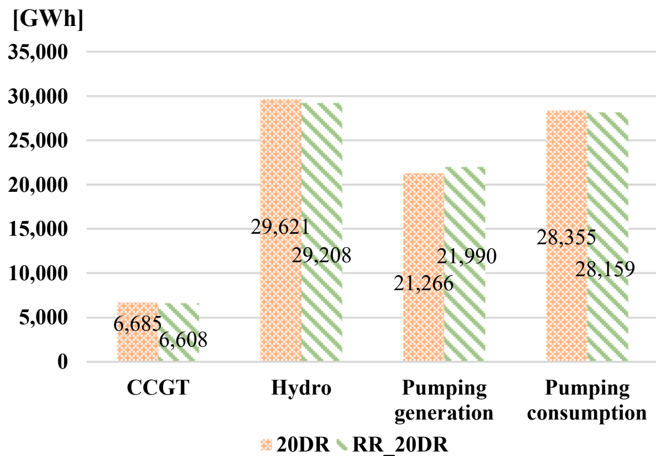

Fig. 4. Wholesale market operation with and without considering reserves market for technologies able to provide reserves with a fixed installed generation technology mix.

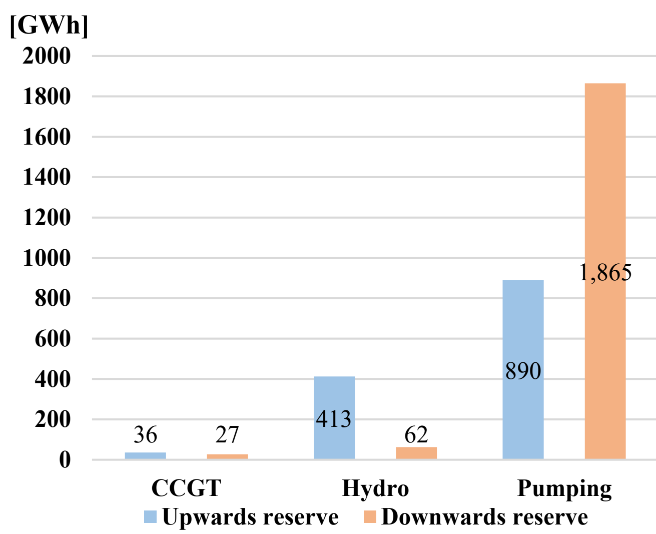

Fig. 5. Upward and downward reserves operation for the RR_20DR with a fixed installed generation technology mix scenario.

planning generation operation and expansion investment. Subsequently, different levels of flexible demand participating in the reserves market would be analyzed, both when the installed electricity generation technology mix is fixed and when it is optimized to compare operation and investment correspondingly. Finally, to determine the impact of demand participating in the wholesale and reserves market on system costs, scenarios where the investment is settled are needed to be able to compare total system costs.

Thus, each scenario is defined by three characteristics: reserves consideration, amount of flexible demand, and the participation of demand in reserves. The first term in the name indicates whether or not the scenario considers the reserves market. If the reserves market is considered, the name begins with RR; in any other case the reserves market is neglected. The second part of the scenario name refers to the percentage of flexible demand considered for heating, cooling, and DHW consumption categories (0DR, 20DR, 40DR, 60DR). In order to be consistent with the EV flexibility estimates presented in Table 7, where the EV is estimated to have around a 60 % of flexibility and see the DR effects with enough perspective, DR usage ranges from 0 % DR to 60 % DR in the other consumption categories, as there is not a clearly-defined amount of DR in 2030. Lastly, the term “dem” is indicated when demand is allowed to participate in the reserves market. Table 8 presents the different scenarios with their main distinguishing features.

The flexible energy available for each DR usage scenario is defined by the input consumption profiles and the preset percentage of DR. Table 9 presents the total flexible energy for each consumption category that applies to both the fixed and the freely installed generation technology mix scenarios for each percentage of DR.

4. Analysis and results

In this section, the results are organized into four blocks to set out the main takeaways of the paper. For this purpose, each block uses the most appropriate scenarios that can be compared and analyzed to draw the relevant conclusions. In brief, the four blocks are: the operation of the system, which uses the fixed installed technology mix scenarios; the total system costs that compare both the fixed and the freely installed generation technology mix scenarios; the investment decisions, which can only be analyzed in the freely installed generation technology mix scenarios; and finally, the flexibility analysis, which in this case is performed over the freely installed generation technology mix scenarios, although conclusions for the fixed installed generation technology mix scenarios are the same.

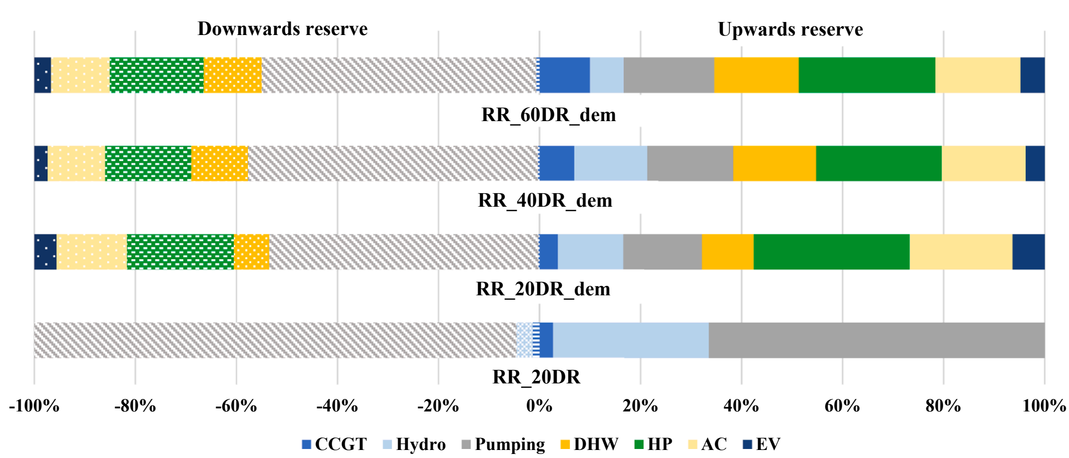

Fig. 6. Reserves market operation for the fixed installed generation technology mix scenarios.

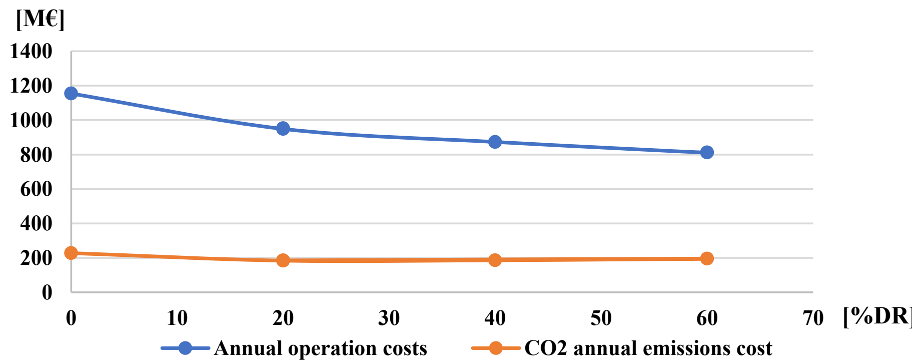

Fig. 7. Operation and CO_2 costs for the wholesale and reserves market in the fixed installed generation technology mix scenarios.

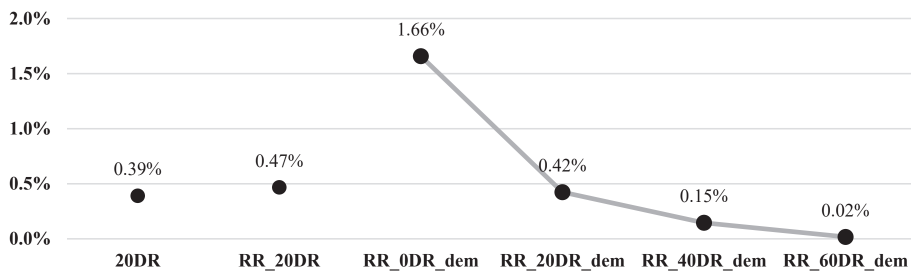

Fig. 8. Solar and wind spillages for fixed installed generation technology mix scenarios.

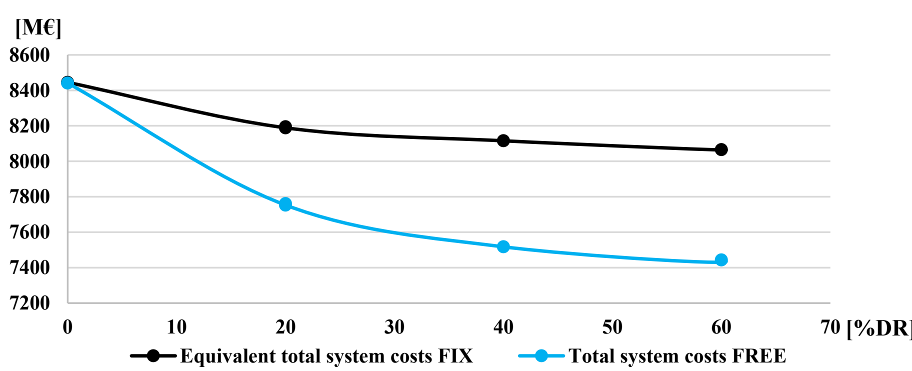

Fig. 9. Total system costs for the fixed and freely installed generation technology mix sensibilities.

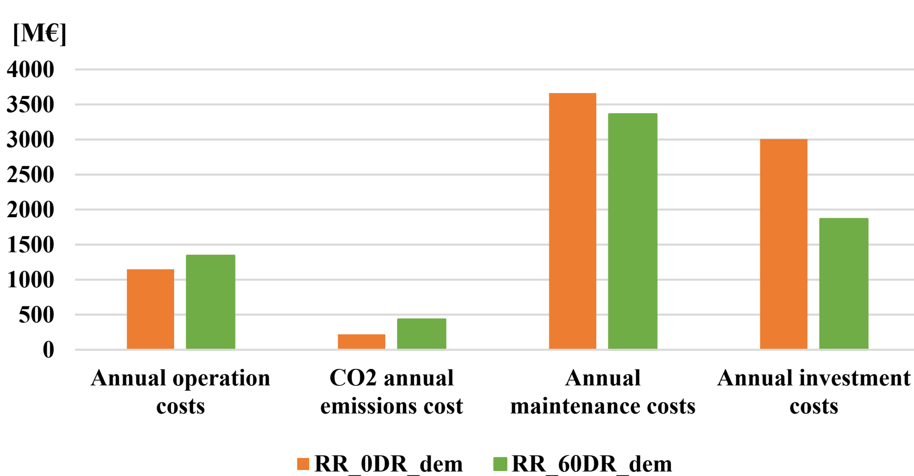

Fig. 10. Comparison from 0 to 60% of DR of system costs for the freely installed generation technology mix sensibilities.

4.1. Operation of the system considering reserves

With the purpose of comparing and analyzing the changes in system operation when considering the reserves and when demand participation in reserves is allowed, fixed generation installed generation technology mix scenarios have been used. Thus, the impact of different investment decisions is avoided.

Technologies that can provide reserves operate differently on the wholesale market when reserves are considered. Fig. 4 compares wholesale market generation with and without considering the reserves market. Fig. 4 show that both CCGT and hydro decrease their operation on the wholesale market to have more availability and increase their generation for the reserves market. However, pumping increases its production in the wholesale market when considering reserves while decreasing their consumption (Fig. 4). Pumping technology has a very high potential to provide downward reserves. It accounts for 95 % of total downward reserve needs. Therefore, its increase in wholesale market generation is to have more capacity available to provide this service (Fig. 5). Conversely, CCGT and hydroelectric technologies are used to a greater extent to provide upwards reserve.

In all scenarios, the downward reserve requirement is greater than the upwards reserve requirement. Pumping is the technology that mainly provides this downward reserve until demand participates in the reserve market. When demand is participating in this market, is responsible for providing about 67 % of the upwards reserve requirement and about 45 % of the downward reserve requirement. This removes a relevant part of the role of pumped storage hydroelectric. Fig. 6 presents the percentage of upward (positive side) and downward (negative side) reserve needs that each available source provides for all scenarios that consider the reserves market. The amount of demand used for upward and downward reserve should always be the same, as shifted demand must be supplied at some point. When demand starts participating in the reserve market it gains relevance, where heating and cooling have flexible demand, the most used consumption sector. However, the more DR that is available in the system does not result in more demand quota providing reserves. As this source defends [13], it is more profitable to use DR for optimizing the wholesale energy market than for balancing needs.

4.2. Wholesale and reserves market system costs and savings

For the fixed installed generation technology mix scenarios, the costs that most differ from one scenario to another are the operation and CO_2 costs. Fig. 7 presents the sum of wholesale and reserves operations as annual operation costs versus the CO_2 costs for all the fixed installed generation technology mix scenarios that consider the reserves market. There are two different scenarios with 20 % DR (RR_20DR and RR_20DR_dem), although they almost overlap, and their difference is not relevant. Reserves market costs account for less than 0,1% of total operating and CO_2 costs. Therefore, its cost does not have a relevant effect on global results.

The decrease in total system costs with the increase in DR is mainly due to the decrease in operating costs in the wholesale market. Undoubtedly, the leap from having no DR at all to having 20 % DR is the most substantial (Fig. 7). It leads to a significant decrease in spillages by making better use of them and preventing other more expensive technologies from producing this energy. The CO2 emission costs remain almost flat, no matter how much available DR there is in the system. This is because with a fixed installed generation technology mix, CCGT operation does not change, and the use of DR is replacing pumping operations.

Fig. 8 presents the percentage of renewable spillages for all scenarios. Under these conditions, DR prioritizes diminishing spillages, and reducing operating costs from the energy market, which results in lower total system costs (Fig. 9). Fig. 8 also reveals that considering reserves increases spillages by 20 % (20DR compared to RR_20DR) if demand does not participate in the reserves markets. Furthermore, spillages are negligible when 60 % DR is available in the system.

Fig. 9 presents the total system costs for the fixed and freely installed generation technology mix scenarios when considering the reserves market. For the fixed installed generation technology mix scenarios, the investment required to attain the pre-installed generation technology mix considered was added to make it equivalent to the total system costs that are being compared.

When increasing from 0 to 60 % DR, the system would experience savings of 5 % with a fixed installed generation technology mix due to the reduction of operating costs. On the other hand, in the case study with the investment decision, savings from considering in advance a percentage of DR from 0 to 60 % would achieve savings of up to 12 % of total expenses, mainly due to decreasing investment costs by considering DR in advance.

Fig. 10 compares the different system costs for the RR_0DR_dem and the RR_60DR_dem scenarios when investment is allowed (freely installed generation technology mix conditions). First, operating costs increase up to 30 % from 0 to 60 % of DR, including CO_2 emissions costs. This is because it tries to avoid technology investment and take advantage of the existing resources with higher operating costs than new technologies. For this same reason, CO_2 costs also increase. Second, the investment costs experience a reduction of 38 % from 0 to 60 % of DR. These costs are responsible for the shape of the total system costs curve (Fig. 9). Finally, maintenance costs also decreased by 8 % from having no DR to counting 60 % of it.

4.3. Generation technology investments with a system that considers the reserves market

To analyze investment decisions, the scenarios where free installation is allowed are assessed. Comparing the scenarios with and without considering reserves (20DR compared to RR_20DR), the total capacity invested for each technology does not undergo relevant changes. This is because reserves represent approximately only 1 % of the total energy requirements. Likewise, DR consideration have a small effect on

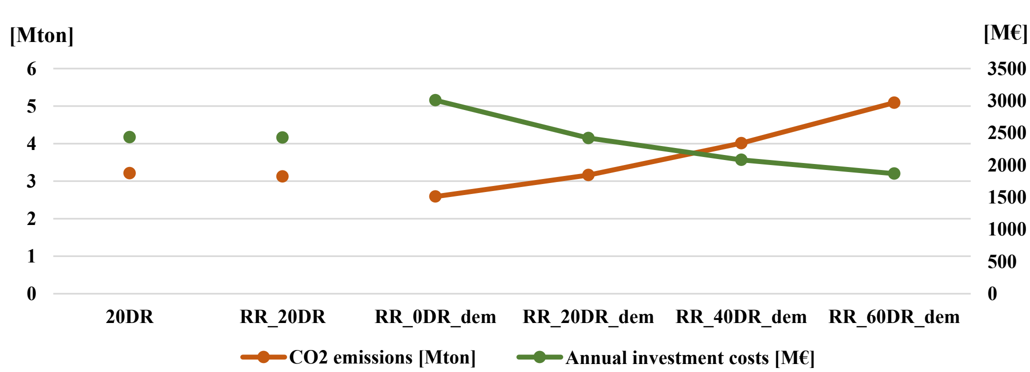

Fig. 11. Investment costs and CO_2 emissions in the freely installed generation technology mix scenarios.

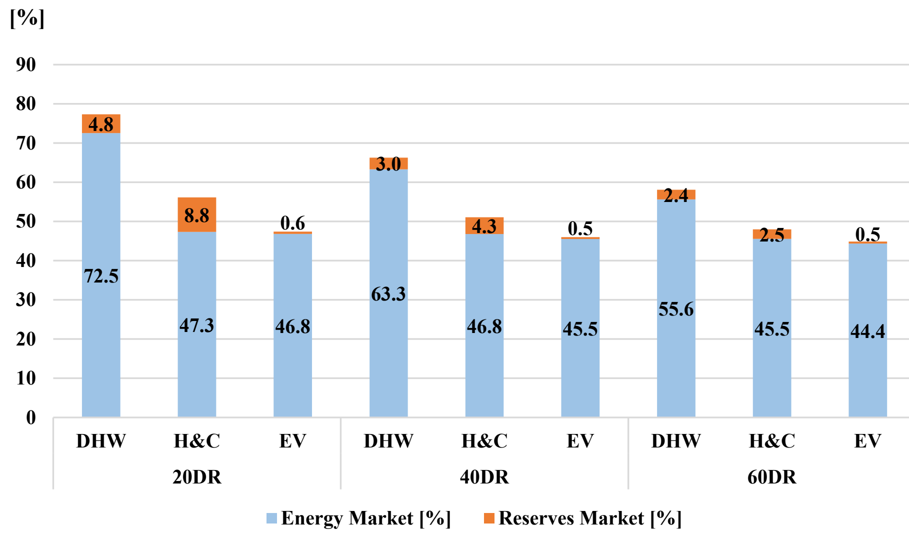

Fig. 12. Flexible demand use with the different consumption categories for the energy and reserves markets for the freely installed generation technology mix scenarios.

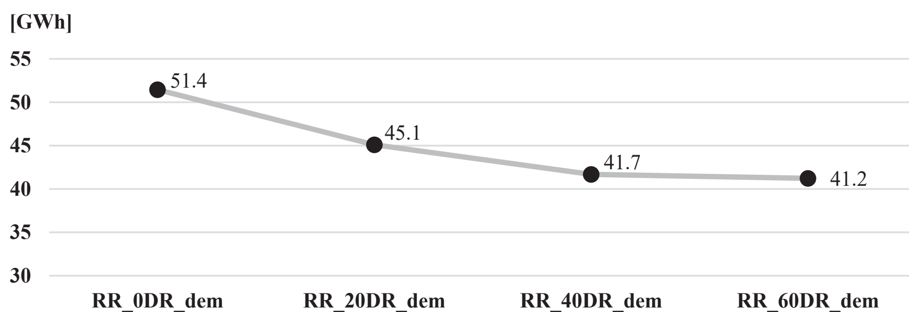

Fig. 13. Peak demand for the freely installed generation technology mix scenarios.

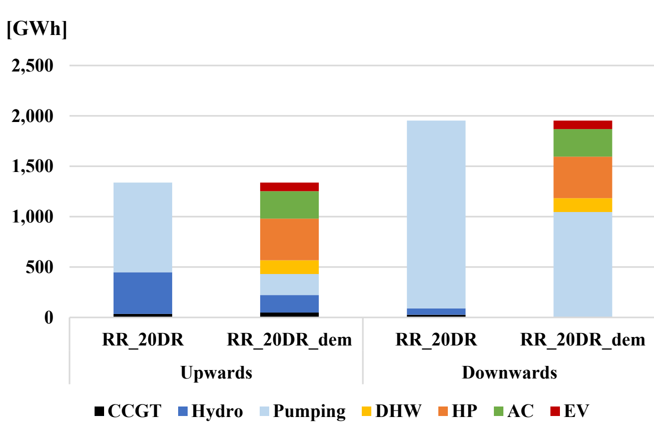

Fig. 14. Upwards and downwards reserves market operation for fix installed generation technology mix scenarios.

investment decisions. When comparing scenarios RR_20DR and RR_20DR_dem which the only difference lies in the demand participation in reserves, 1 % of technology investment expenditures are avoided, mainly from renewables, as energy requirements decrease with the increase in DR. Furthermore, the greater the availability of DR in the system, the less investment is required. DR mainly reduces investment in firm capacity, thus avoiding pumping hydroelectric storage installation. Therefore, the lower the investment in pumping, the higher the use of CCGT or other pollutant technologies that are already available in the system to provide energy during sun and wind scarcity periods. Hence, more CO_2 emissions are generated, as this study concludes for the northern European energy system[63]. This effect is presented in Fig. 11. A trade-off between costs and emissions can be seen in around 33 % DR penetration.

4.4. Flexible demand participation in energy and reserves markets

Fig. 12 represents the amount of flexibility used and how much it has been used for power and for the reserves market from the total available flexibility of each consumption category for the freely-installed generation technology mix scenarios. This has been done by comparing the energy moved with respect to the non-flexible profile consumption.

An increase in available DR does not mean an increase in DR opportunities. In fact, the flexible demand used according to the flexible demand available is decreasing for the sum of both markets when there is more DR in the system. This means that a specific amount of flexibility is needed in the system. One relevant constraint that explains this behavior is that all flexible demand that is not consumed at its scheduled hour must be consumed at another time. Hence, results reveal that part of the flexible demand is not of interest to move in any of the markets due to this limit.

Analyzing this figure in detail, the different consumption categories also have different potential providing energy services. DHW use on average a 67 % of their total available flexibility, while H&C and EV, on average, use close to 50 % of their total available flexibility. However, H&C provides more in relative and absolute terms (Fig. 14) in reserve services. This is due to a higher amount in GWh of flexible demand available from this category (Table 9). The methodology of considering temperature constraints limits the changeable demand possibilities, thus reducing its possibilities on the wholesale market and facilitating opportunities on the reserves market compared to EV and DHW.

In addition, DR decreases firm capacity needs, which are directly proportional to the decrease in peak demand (Fig. 13). About 60 % DR decreases peak demand by 20 %. Thus, the more DR there is in the system, the less pumping hydroelectric storage investment there is. Hence, the reserves market remains in the background due to the use of DR.

Fig. 14 compares the two scenarios with 20DR that consider reserves, but one has demand participation and the other does not. When demand participates in the reserves market for upward reserve, it supplies around 67 % of the needs of total reserve needs. On the other hand, it supplies around 45 % of the downward reserve needs, although it merits mention that in absolute terms, both directions use the same amount of demand participation due to model constraints, but the share of upward reserve is higher, meaning that less total energy is required.

5. Conclusions and future work

This study analyzes the impact of considering balancing services in the operation and investment decisions when planning the future electricity system, besides the role of DR and its effect when participating in the energy and reserves markets.

Thus, this study, proves that there is a difference between whether or not the reserves market is considered for system operation and investments. The operation of the sources can provide changes in reserves. CCGT and hydroelectric reduce their generation in the energy market in order to have more available energy to provide upward reserves. In contrast, pumping storage increases its generation and reduces its consumption for the energy market in order to be able to provide more downward reserve. Regarding CO_2 emissions, their decrease is not directly related to a decrease in spillages or an increase in DR available in the system. The reduction of CO_2 emissions implies an increase in total system costs. When the objective is to minimize the system costs, the increase of available DR raises the usage of existing polluting technologies to avoid investments in storages. Therefore, in the case where lowering CO_2 emissions was the target, an additional constraint should be taken into consideration to optimize investment and operation from that perspective instead of from the cost minimization point of view. Investment decisions about generation technologies do not change due to considering or not considering reserves, as this market represents only 1 % of total energy supply needs.

This study demonstrates that demand participation in the reserves market has a non-neglectable role. Although, only a 1 % of technology investment expenditures can be avoided and the percentage of flexible demand used for reserves is low compared to wholesale use, more than 45 % of the reserve energy needs could be met with demand assets. Results show that H&C is the category that provides the majority of energy in reserves due to their larger energy presence in the system. However, results also reflect that the two other categories, DHW and EV, offer more relative flexibility. This is because their demand has fewer shifting constraints, whereas H&C is limited by outdoor temperatures and indoor comfort maintenance, which constrains the possibilities of shifting demand.

Finally, DR participating in the energy and reserves market would be responsible for savings of at least 5 % whether or not investment considers new generation technologies. If DR availability was considered before technology investments are decided, up to 12 % of total system costs could be saved with a high penetration of DR (60 % of its total potential) although CO_2 emissions increase by 95 %. A decision between desired savings and emissions establishes a trade-off point of around 33 % DR participation from DHW and H&C demands. This finding has important policy implications since it shows that while demand response leverages existing infrastructure, it should be complemented with new storage investments (against the minimum cost alternative) to deal with the increase in emissions effectively. Due to the use limitations established for the different flexibility sources, the estimated total system savings are below what literature forecasts (between 15 and 30 %).

There are many other services where DR could add value to the system when the aggregator figure is more mature, such as congestion management. Therefore, all these services should also be assessed. Other future lines to continue with this study would be to achieve DR operating and investment costs to be able to optimize the amount of DR in the system and include other sources of flexible demand, such as industrial processes or refrigeration, that could increase total system savings.

CRediT authorship contribution statement

Teresa Freire-Barceló: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Francisco Martín-Martínez:** Funding acquisition, Supervision, Validation, Writing – review & editing. **Álvaro Sánchez-Miralles:** Conceptualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

This paper has been partially financed by ReDREAM project, funded by the European Union's Horizon 2020 research and innovation programme (Horizon2020 Framework Programme) under grant agreement number 957837.

Teresa Freire-Barcelo reports financial support was provided by Horizon 2020 Framework Programme. Francisco Martin-Martinez reports financial support was provided by Horizon 2020 Framework Programme. Alvaro Sanchez-Miralles reports financial support was provided by Horizon 2020 Framework Programme.

References

[1] European Parliament, Council of the EU, Directive (EU) 2019/944 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU, Official Journal of the European Union. (2019) 18. https://doi.org/http://eur-lex.europa.eu/pri/en/oj/dat/2003/l_285/l_28520031101en00330037.pdf.
[2] Meeus L, Nouicer A. The EU Clean Energy Package 2020. https://doi.org/10.2870/013463.
[3] DNV, Aurora Sáez Armenteros, Hans de Heer, SmartEN 2030 DSF quantification of benefits in the EU, (n.d.). chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://smarten.eu/wp-content/uploads/2022/09/SmartEN-DSF-benefits-2030-Report_DIGITAL.pdf (accessed April 19, 2023).
[4] Bessa RJ, Matos MA. Optimization models for EV aggregator participation in a manual reserve market. IEEE Trans Power Syst 2013;28(3):3085–95.
[5] Vagropoulos SI, Bakirtzis AG. Optimal bidding strategy for electric vehicle aggregators in electricity markets. IEEE Trans Power Syst 2013;28:4031–41. https://doi.org/10.1109/TPWRS.2013.2274673.
[6] Angenendt G, Merten M, Zurmühlen S, Sauer DU. Evaluation of the effects of frequency restoration reserves market participation with photovoltaic battery energy storage systems and power-to-heat coupling. Appl Energy 2020;260. https://doi.org/10.1016/j.apenergy.2019.114186.
[7] Misconel S, Zöphel C, Möst D. Assessing the value of demand response in a decarbonized energy system – A large-scale model application. Appl Energy 2021;299. https://doi.org/10.1016/j.apenergy.2021.117326.
[8] Dietrich K, Latorre JM, Olmos L, Ramos A. Demand response in an isolated system with high wind integration. IEEE Trans Power Syst 2012;27:20–9. https://doi.org/10.1109/TPWRS.2011.2159252.
[9] Explicit Demand Response in Europe Mapping the Markets 2017, 2017.
[10] Rancilio G, Rossi A, Falabretti D, Galliani A, Merlo M. Ancillary services markets in europe: Evolution and regulatory trade-offs. Renew Sustain Energy Rev 2022;154. https://doi.org/10.1016/j.rser.2021.111850.

[11] Freire-Barceló T, Martín-Martínez F, Sánchez-Miralles Á. A literature review of Explicit Demand Flexibility providing energy services. Electr Pow Syst Res 2022; 209:107953. https://doi.org/10.1016/j.epsr.2022.107953.
[12] R. Bray, B. Woodman, Barriers to Independent Aggregators in Europe, n.d.
[13] Feuerriegel S, Neumann D. Integration scenarios of Demand Response into electricity markets: Load shifting, financial savings and policy implications. Energy Policy 2016;96:231–40. https://doi.org/10.1016/j.enpol.2016.05.050.
[14] Boldrini A, Jiménez Navarro JP, Crijns-Graus WHJ, Van den Broek Ma. The role of district heating systems to provide balancing services in the European Union. Renew Sustain Energy Rev 2022;154. https://doi.org/10.1016/j.rser.2021.111853.
[15] Diaz-Londono C, Correa-Florez CA, Vuelvas J, Mazza A, Ruiz F, Chicco G. Coordination of specialised energy aggregators for balancing service provision, Sustainable Energy. Grids and Networks 2022;32. https://doi.org/10.1016/j.segan.2022.100817.
[16] Utama C, Troitzsch S, Thakur J. Demand-side flexibility and demand-side bidding for flexible loads in air-conditioned buildings. Appl Energy 2021;285. https://doi.org/10.1016/j.apenergy.2020.116418.
[17] Li R, Satchwell AJ, Finn D, Christensen TH, Kummert M, Le Dréau J, et al. Ten questions concerning energy flexibility in buildings. Build Environ 2022;223. https://doi.org/10.1016/j.buildenv.2022.109461.
[18] De Zotti G, Pourmousavi SA, Morales JM, Madsen H, Poulsen NK. A control-based method to meet TSO and DSO ancillary services needs by flexible end-users. IEEE Trans Power Syst 2020;35:1868–80. https://doi.org/10.1109/TPWRS.2019.2951623.
[19] De Zotti G, Pourmousavi SA, Madsen H, Kjolstad Poulsen N. Ancillary services 4.0: A top-to-bottom control-based approach for solving ancillary services problems in smart grids. IEEE Access 2018;6:11694–706. https://doi.org/10.1109/ACCESS.2018.2805330.
[20] Barbero M, Corchero C, Canals Casals L, Igualada L, Heredia F-J. Critical evaluation of European balancing markets to enable the participation of demand aggregators. Appl Energy 2020.
[21] E. O'shaughnessy, M. Shah, The Demand-Side Opportunity: The Roles of Distributed Solar and Building Energy Systems in a Decarbonized Grid, 2019. https://www.nrel.gov/docs/fy21osti/80527.pdf.
[22] Directorate-General for Mobility and Transport, European Alternative Fuels Observatory, (n.d.). https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road (accessed April 20, 2023).
[23] Comunidad de Madrid, Programas de ayudas a Renovables en Autoconsumo, Almacenamiento y Sistemas Térmicos, (n.d.). https://ayudasrenovablesmadrid.com/termicas/programa-6-sistemas-t%C3%A9rmicos-renovables (accessed April 20, 2023).
[24] IDAE, PROGRAMA MOVES III, (n.d.). https://www.idae.es/ayudas-y-financiacion/para-movilidad-y-vehiculos/programa-moves-iii (accessed April 20, 2023).
[25] J. Vasiljevska, F. Gangale, L. Covrig, A. Mengolini, Smart Grids and Beyond: An EU research and innovation perspective, 2021. https://publications.jrc.ec.europa.eu/repository/handle/JRC125980 (accessed April 20, 2023).
[26] Red Eléctrica de España, ESIOS, (2022). https://www.ree.es/es/actividades/operacion-del-sistema-electrico (accessed June 6, 2022).
[27] Kühnlenz F, Nardelli PHJ, Karhinen S, Svento R. Implementing flexible demand: Real-time price vs. market integration. Energy 2018;149:550–65. https://doi.org/10.1016/j.energy.2018.02.024.
[28] Yang S, Tan Z, Liu ZX, Lin H, Ju L, Zhou F, et al. A multi-objective stochastic optimization model for electricity retailers with energy storage system considering uncertainty and demand response. J Clean Prod 2020;277:124017. https://doi.org/10.1016/j.jclepro.2020.124017.
[29] Bruninx K, Dvorkin Y, Delarue E, D'haeseleer W, Kirschen DS. Valuing demand response controllability via chance constrained programming. IEEE Trans Sustain Energy 2018;9(1):178–87.
[30] Anwar MB, Qazi HW, Burke DJ, O'Malley MJ. Harnessing the flexibility of demand-side resources. IEEE Trans Smart Grid 2019;10:4151–63. https://doi.org/10.1109/TSG.2018.2850439.
[31] Roos A, Ottesen SO, Bolkesjø TF. Modeling consumer flexibility of an aggregator participating in the wholesale power market and the regulation capacity market. Energy Procedia 2014;58:79–86. https://doi.org/10.1016/j.egypro.2014.10.412.
[32] Ottesen SØ, Tomasgard A, Fleten SE. Prosumer bidding and scheduling in electricity markets. Energy 2016;94:828–43. https://doi.org/10.1016/j.energy.2015.11.047.
[33] Liu G, Tomsovic K. A full demand response model in co-optimized energy and reserve market. Electr Pow Syst Res 2014;111:62–70. https://doi.org/10.1016/j.epsr.2014.02.006.
[34] Doorman GL, Nygreen B. An integrated model for market pricing of energy and ancillary services. Electr Pow Syst Res 2002;61:169–77.
[35] Godoy-gonzález D, Gil E, Gutiérrez-alcaraz G. Ramping ancillary service for cost-based electricity markets with high penetration of variable renewable energy. Energy Econ 2020;85:104556. https://doi.org/10.1016/j.eneco.2019.104556.
[36] Iria J, Soares F, Matos M. Optimal bidding strategy for an aggregator of prosumers in energy and secondary reserve markets. Appl Energy 2019;238:1361–72. https://doi.org/10.1016/j.apenergy.2019.01.191.
[37] Iria JP, Soares FJ, Matos MA. Trading small prosumers flexibility in the energy and tertiary reserve markets. IEEE Power and Energy Society General Meeting 2018-Janua 2018:1–5. https://doi.org/10.1109/PESGM.2017.8274488.
[38] Majzoobi A, Khodaei A. Application of microgrids in supporting distribution grid flexibility. IEEE Trans Power Syst 2017;32:3660–9. https://doi.org/10.1109/TPWRS.2016.2635024.
[39] Gazijahani FS, Salehi J. IGDT-based complementarity approach for dealing with strategic decision making of price-maker vpp considering demand flexibility. IEEE Trans Industr Inform 2020;16:2212–20. https://doi.org/10.1109/TII.2019.2932107.
[40] Henriquez R, Wenzel G, Olivares DE, Negrete-Pincetic M. Participation of demand response aggregators in electricity markets: Optimal portfolio management. IEEE Trans Smart Grid 2018;9:4861–71. https://doi.org/10.1109/TSG.2017.2673783.
[41] Talari S, Yazdaninejad M, Haghifam MR. Stochastic-based scheduling of the microgrid operation including wind turbines, photovoltaic cells, energy storages and responsive loads. IET Gener Transm Distrib 2015;9:1498–509. https://doi.org/10.1049/iet-gtd.2014.0040.
[42] Manner P, Salmelin J, Honkapuro S, Alapera I, Annala S. A novel method to utilize direct electrical space heating for explicit demand response purposes -proof of concept. IEEE PES Innovative Smart Grid Technologies Conference Europe 2020-Octob 2020:86–90. https://doi.org/10.1109/ISGT-Europe47291.2020.9248893.
[43] Y. Chen, U. Hashmi, J. Mathias, A. Busic, S. Meyn, Y. Chen, U. Hashmi, J. Mathias, A. Busic, S. Meyn, D. Control, Distributed Control Design for Balancing the Grid Using Flexible Loads, HAL. Volume on (2018) 383–411.
[44] Francisco Martín Martínez, Álvaro Sánchez Miralles, Michel Rivier Abad, Modeling tools for planning and operation of DERs and their impact in microgrids and centralized sources, 16 (2017). https://doi.org/10.32964/tj16.5.
[45] T. Gerres, J.P.C. Ávila, F.M. Martínez, M.R. Abbad, R.C. Arín, Á.S. Miralles, T.G. San Román, "Rethinking the electricity market design: Remuneration mechanisms to reach high RES shares. Results from a Spanish case study" (Energy Policy (2019) 129 (1320–1330), (S0301421519301995), (10.1016/j.enpol.2019.03.034)), Energy Policy. 131 (2019) 434. https://doi.org/10.1016/j.enpol.2019.04.014.
[46] Freire-Barceló T, Martín-Martínez F, Sánchez-Miralles Á, Rivier M, Román TGS, Huclin S, et al. Storage and demand response contribution to firm capacity: analysis of the Spanish electricity system. Energy Rep 2022;8:10546–60. https://doi.org/10.1016/j.egyr.2022.08.014.
[47] Martín-Martínez F, Sánchez-Miralles A, Rivier M, Calvillo CF. Centralized vs distributed generation. A model to assess the relevance of some thermal and electric factors. Application to the Spanish case study. Energy 2017;134:850–63. https://doi.org/10.1016/j.energy.2017.06.055.
[48] Godoy-González D, Gil E, Gutiérrez-Alcaraz G. Ramping ancillary service for cost-based electricity markets with high penetration of variable renewable energy. Energy Econ 2020;85. https://doi.org/10.1016/j.eneco.2019.104556.
[49] Roos A, Ottesen SO, Bolkesjø TF. Modeling consumer flexibility of an aggregator participating in the wholesale power market and the regulation capacity market. Energy Procedia, Elsevier Ltd 2014:79–86. https://doi.org/10.1016/j.egypro.2014.10.412.
[50] Huclin S, Chaves JP, Ramos A, Rivier M, Freire-Barceló T, Martín-Martínez F, et al. Exploring the roles of storage technologies in the Spanish electricity system with high share of renewable energy. Energy Rep 2022;8:4041–57. https://doi.org/10.1016/j.egyr.2022.03.032.
[51] M. Rivier, F. Martín-Martínez, T. Freire-Barceló, Solar and wind production profiles and 2030 disaggregated electricity demand profiles to feed the SPLODER generation expansion planning model, 2022. https://www.iit.comillas.edu/publicacion/informe/es/306/Solar_and_wind_production_profiles_and_2030_disaggregated_electricity_demand_profiles_to_feed_the_SPLODER_generation_expansion_planning_model.
[52] Red Eléctrica de España, REE, (2022). https://www.ree.es/es/clientes/generador/acceso-conexion/conoce-la-capacidad-de-acceso.
[53] Penizzotto F, Pringles R, Olsina F. Real options valuation of photovoltaic power investments in existing buildings. Renew Sustain Energy Rev 2019;114:109308.
[54] Henriquez-Auba R, Hidalgo-Gonzalez P, Pauli P, Kalathil D, Callaway DS, Poolla K. Sharing economy and optimal investment decisions for distributed solar generation. Appl Energy 2021;294. https://doi.org/10.1016/j.apenergy.2021.117029.
[55] Aghaei J, Bozorgavari SA, Pirouzi S, Farahmand H, Korpås M. Flexibility planning of distributed battery energy storage systems in smart distribution networks. Iranian Journal of Science and Technology - Transactions of Electrical Engineering 2020;44:1105–21. https://doi.org/10.1007/s40998-019-00261-z.
[56] Golmohamadi H. Demand-side flexibility in power systems: A survey of residential, industrial, commercial, and agricultural sectors. Sustainability (Switzerland) 2022; 14(13):7916.
[57] Gobierno de España Ministerio para la transición ecológica y el reto demográfico y IDAE, Hoja de ruta del autoconsumo, 2021. https://www.miteco.gob.es/es/ministerio/planes-estrategias/hoja-ruta-autoconsumo/default.aspx.
[58] Red Eléctrica de España, ESIOS, (2019). https://www.esios.ree.es/es/mapas-de-interes.
[59] Ministerio para la Transición Ecológica y el Reto Demográfico, Plan Nacional Integrado de Energía y Clima 2021-2030, Spain, 2020. https://www.idae.es/informacion-y-publicaciones/plan-nacional-integrado-de-energia-y-clima-pniec-2021-2030.
[60] International Energy Agency, Global EV Outlook 2021 Accelerating ambitions despite the pandemic, 2021. https://www.iea.org/reports/global-ev-outlook-2021.
[61] Ministerio del interior, Gobierno de España, DGT, https://Sedeapl.Dgt.Gob.Es/WEB_IEST_CONSULTA/Subcategoria.Faces. (2020). https://sedeapl.dgt.gob.es/WEB_IEST_CONSULTA/subcategoria.faces (accessed October 10, 2022).
[62] Ministerio del interior, Gobierno de España, Inspección Técnica de Vehículos (ITV), Https://Industria.Gob.Es/Calidad-Industrial/Vehiculos/Paginas/Inspeccion-Tecnica-Vehiculos.Aspx. (2020). https://industria.gob.es/Calidad-Industrial/vehiculos/Paginas/inspeccion-tecnica-vehiculos.aspx (accessed October 10, 2022).
[63] Kirkerud JG, Nagel NO, Bolkesjø TF. The role of demand response in the future renewable northern European energy system. Energy 2021;235:121336.