Long-Run Cost-Benefit Analysis of Demand Response for the European System

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Abstract—**The operation of power systems faces great challenges as the penetration of variable renewable energy keeps increasing rapidly. Meanwhile, the electrification of transportation and heating systems can increase future peak demand. As a result, grid infrastructures will need to be reinforced, including construction of combustion turbines in order to meet peak demand and offer flexibility to the system, and investment in transmission and distribution lines. However, there exists massive flexibility potential on the demand side, which can be exploited in order to reduce or postpone the upgrade of current power systems. Meanwhile, investment in smart meters is necessary to enable demand response. In this paper, we build a capacity expansion model for the European system and carry out a cost-benefit analysis considering the scenario of year 2050. We identify substantial flexibility potential in the residential sector and we find that the investment cost in smart meters can be justified from the perspective of energy suppliers.**

I. INTRODUCTION

The large-scale integration of renewable energy and demand response resources in smart grids is progressing at an unprecedented pace. Europe is leading this endeavor at a global scale through the 20-20-20 targets[1] of the European Commission [1]. The electrification of transportation and heating systems can increase future peak demand, even though the net demand for energy from conventional generators may decrease due to increasing renewable production. The growth of peak demand could necessitate infrastructure upgrades, including the construction of combustion turbines that may operate for just a few hours per year in order to meet peak demand, and investment in transmission and distribution lines. Yet this argument is based on the fundamental assumption that additional capacity is required in order to satisfy inflexible end-use demand, an assumption which may need to be revisited since there exists massive flexibility potential on the demand side. According to [2], the aggregated theoretical DR potential in Europe amounts to an hourly average of 93 GW for load reduction and 247 GW for load increase.

Demand response carries various benefits, such as (i) benefits from relative and absolute reductions in electricity demand; (ii) benefits resulting from short-run marginal cost savings; (iii) benefits in terms of displacing new plant investment by shifting peak demand; etc. The major costs for enabling demand response that we focus on in this paper are investment costs in smart meters. There are many studies on the cost-benefit analysis of demand response. In [3], the authors review studies focused on the UK and present a new quantitative model for assessing economic welfare gain. It is demonstrated that the economic case for DR in UK electricity markets is positive. A report by the Department for Business, Energy & Industrial Strategy of the UK draws the same conclusion for the domestic sector [4]. Benefits of DR are also measured in the future Finish energy system, by modelling demand shifting in the residential and commercial sector. A more realistic model of load shifting and shedding mechanisms is presented in [5], where the economic potential is evaluated by considering different future scenarios of Germany. In [6], the authors carry out the study from a system perspective for the Dutch system and assess the long-run demand response benefits in terms of grid value and market value. However, most of the studies are conducted at a single country level and to the authors best knowledge, the only paper at the European level is [7], which analyzes the cost of smart meters and the benefits from dynamic tariffs for the European system. However, in this study the increasing penetration of renewable production in the future is not taken into consideration.

In this paper, we aim at filling the following research gaps. Firstly, the assessment of the costs and benefits of demand response is performed at the Europe level and considers the scenario of year 2050. Secondly, investment in grid infrastructures and generation operating costs are both accounted for in the analysis. Thirdly, economic benefits in different sectors (i.e., industrial, commercial and residential) are identified. Lastly, a sensitivity analysis on the level of a carbon cap is conducted. The rest of the paper is organized into three sections. The next section describes the flexible consumers that we consider in this study and develops a capacity expansion model for the European system. The discussion moves on to analyze the results. The final section of the paper offers some concluding thoughts.

II. METHODOLOGY

We consider the capacity expansion problem for the European system (including 27 member countries) under the scenario of year 2050, in order to determine capital costs

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[1] The 20-20-20 targets aim at reducing greenhouse gases to at least 20% of 1990 levels, reducing energy consumption by 20% of projected 2020 levels and increasing use of renewables (wind, solar, biomass, etc.) to 20% of total energy production

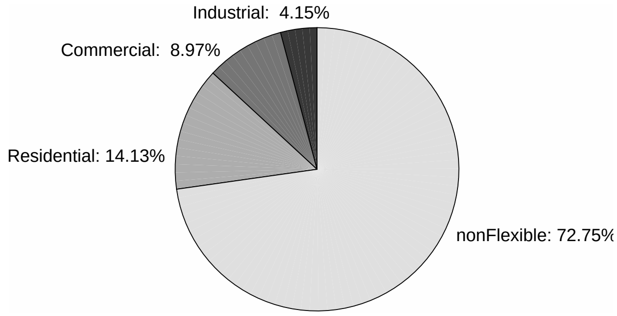

Fig. 1. Portion of flexible energy in each sector of the European system.

in generation capacity and operating costs. The results of a system with inelastic demand are compared with those of a system with flexible demand. Demand flexibility, including 30 types of consumers in the industrial, commercial and residential sectors, is modeled as a perfect storage resource. The interpretation is that consumers require a certain amount of energy from the grid each day, but are flexible regarding the exact timing of consumption. The modeling approach and data are detailed as follows.

A. Data

Solar and wind production profiles, and total load profiles of each country in the year 2015 are available from the ENTSOE Transparency Platform with hourly resolution [8]. The data is scaled up to represent the year 2050 based on [9].

The 30 types of flexible consumers in the industrial, commercial and residential sectors are detailed in [2]. The maximum consumption rate and average daily energy need of each of the 30 types are calibrated for every country based on [2]. Flexible energy in the European system is shown in Fig. 1, in which the percentage of each sector is calculated as the ratio of average daily flexible energy need to average daily total energy need. The pie chart shows that around one quarter of demand is flexible, and that the residential sector accounts for the major part.

Fig. 2 describes the portion of flexible energy in each country in more detail. One can observe that flexible energy mainly lies in the residential sector in most countries. In terms of overall flexible energy, the portion peaks at 34.88% in Greece and is as low as 19.04% in the Czech Republic.

In the capacity expansion model, we consider five technologies, whose specifications are available in table I. The investment costs are conversed to hourly running costs assuming a rate of return of 8%, an investment lifetime of 50 years and an overnight cost of 3430 €/kW, 1715 €/kW, 536 €/kW and 214 €/kW respectively.

B. Comparison Criteria

The benefits of demand response which we focus on quantifying include the following potential cost savings.

1) Generation capital costs: savings in investment in the generation capacity of each technology;

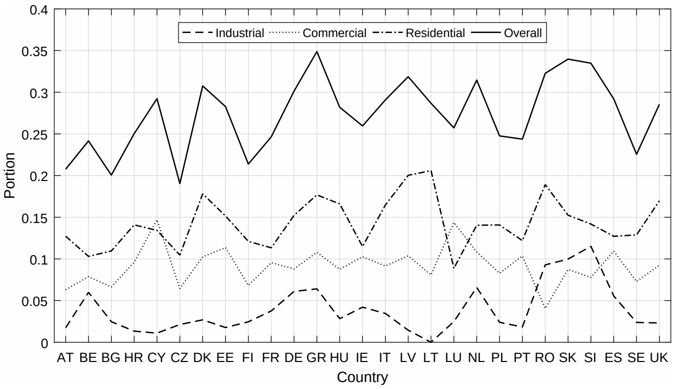

Fig. 2. Portion of flexible energy in each sector of each country.

TABLE I
SPECIFICATIONS OF FIVE TECHNOLOGIES.

Technology	Marginal Cost (€/MWh)	Investment Cost (€/MWh)	Carbon Content (tCO_2/MWh)
Nuclear	6.5	32	0
Coal	25	16	0.85
Gas	80	5	0.34
Oil	160	2	0.63
DR	1000	0	0

2) Generation operating costs: the operating cost reduction related to the production of electricity;
3) Low-voltage grid costs: the deferral of the investment in low-voltage lines and cables.

C. Model

The objective is to minimize generation capital costs and generation operating costs:

$$\sum_{t=1}^{T}\sum_{g\in G}\Big(Cap_g \cdot InvCost_g + MC_g \cdot Prod_{g,t}\Big) \tag{1}$$

where G is the set of technologies, T is the horizon, Cap_g is the capacity invested in generator g, and $Prod_{g,t}$ is the power production of generator g at hour t. $InvCost_g$ and MC_g are available in table I.

The power production of technology g cannot exceed its capacity:

$$Prod_{g,t} \leq Cap_g, g \in G, t = 1, \ldots, T \tag{2}$$

In a system with inelastic demand, the power balance constraint is represented by

$$D_t = \sum_{g\in G} Prod_{g,t} + RenewProd_t - RenewShed_t, t = 1, \ldots, T \tag{3}$$

where D_t is the total load at hour t, $RenewProd_t$ is solar and wind production at hour t, and $RenewShed_t$ is the amount of renewable production curtailment.

In a system with demand response, Eq. (3) is replaced by Eqs. (4) to (6).

$$D_{nonflex,t} + \sum_{c \in C} D_{c,t} \tag{4}$$
$$= \sum_{g \in G} Prod_{g,t} + RenewProd_t - RenewShed_t, t = 1, \ldots, T$$

where C is the set of flexible consumer classes and $D_{c,t}$ is the power supplied to consumer class c at hour t.

The energy need of each flexible consumer class is satisfied on a daily basis.

$$\sum_{t=24 \cdot d+1}^{24 \cdot d+24} D_{c,t} = EnergyNeed_c, c \in C, d = 0, \ldots, 364 \tag{5}$$

Power supplied to consumer class c at hour t is constrained by a maximum power rate.

$$D_{c,t} \leq PowerRate_c, c \in C, t = 1, \ldots, T \tag{6}$$

The following non-negativity constraints are required:

$$Prod_{g,t}, RenewShed_t, D_{c,t}, Cap_g \geq 0,$$
$$g \in G, c \in C, t = 1, \ldots, T$$

The model is built with a yearly horizon and hourly resolution, and each country is solved for separately. Low-voltage grid costs are calculated *ex post*.

III. Results

In this section, we first present the capacity investment decision and cost savings when the flexibility of all three sectors are mobilized. The contribution of each sector is identified. Sensitivity analysis on the carbon emission cap is conducted and the investment cost in smart meters is estimated. Finally, the investment cost in low-voltage grid infrastructure is discussed.

A. Capacity Investment Decision and Cost Savings

As shown in Fig. 3, at the European level, more nuclear capacity is invested for the case with mobilized demand response. In contrast, a system with inelastic demand sees more coal, gas and oil capacity. Moreover, less total capacity is required if flexibility is mobilized.

In terms of cost savings as a result of implementing demand response, total cost savings amount to 6.09%, in which savings from generation capital costs represent 0.91% while savings from generation operating costs constitute 5.18%.

More specific cost savings per country are described in Fig. 4. It is possible that generation capital costs are higher in some countries when demand response is mobilized, while total costs are uniformly lower in all countries. Greece witnesses the most substantial total cost savings, which amount to 22.31%, whereas the lowest is 1.6% in Finland. The average of total cost savings in each country equal 6.79%.

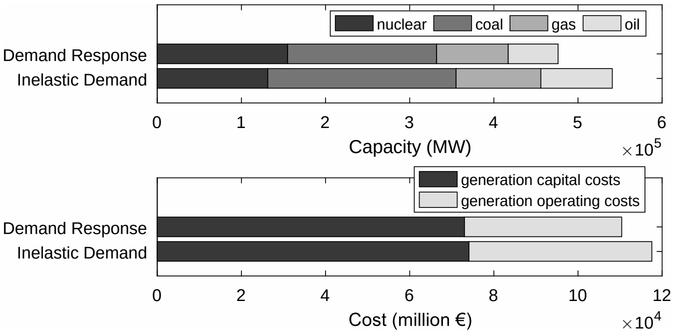

Fig. 3. Comparison of costs and capacity investment decisions for the European system.

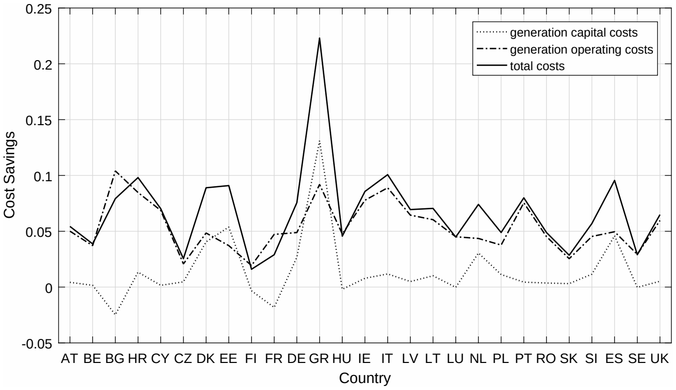

Fig. 4. Cost saving in each country in terms of proportion.

B. Contributions of Sectors to Cost Savings

We proceed by considering the contributions of different combinations of sectors in terms cost savings and the reduction of renewable curtailment. The results are shown in table II. It is clear from the table that by merely mobilizing the residential sector, a total cost saving of 5.26% can be achieved, which accounts for 86.4% of the cost saving potential across all sectors. This observation emphasize the great potential of the residential sector in delivering the majority of possible benefits from demand response.

C. Sensitivity Analysis on Carbon Emissions Cap

In this case study, we first calculate the CO_2 emissions of each country in the cost-optimal results when the demand is inelastic, which is regarded as a reference scenario in terms of carbon emissions. Then the cap is reduced with a step of 10% up to 0%. In table III, we compare the results under both policies in different carbon emissions scenarios. It can be seen that the cost savings from demand response are more substantial when the carbon emissions cap becomes tighter. This indicates that demand response facilitates a low-carbon society by offering flexibility to the power system, with the potential benefits amounting close to 10%.

D. Investment in Smart Meters

We adopt the same approach as in [7] in order to estimate the cost of installing smart meters. The costs of domestic

TABLE II
COST SAVINGS AND REDUCTION OF RENEWABLE CURTAILMENT CONSIDERING DIFFERENT SECTOR COMBINATIONS.

Sectors	Capital Cost Saving (million €)	Operating Cost Saving (million €)	Total Cost Saving (million €)	Total Cost Saving (%)	Renewable Curtailment Reduction (%)
I	286.66	723.18	1009.84	0.86	3.06
C	703.8	3411.05	4114.85	3.50	21.25
R	865.36	5314.71	6180.06	5.26	36.13
IC	862.94	3877.56	4740.50	4.03	23.02
IR	882.38	5660.4	6542.78	5.57	37.36
CR	993.84	6054.53	7048.37	6.00	41.25
ICR	1068.91	6084.96	7153.87	6.09	41.93

TABLE III
COST SAVINGS IN DIFFERENT CARBON EMISSION CAP SCENARIOS.

Scenarios (% of Ref.)	Capital Cost Saving (million €)	Operating Cost Saving (million €)	Total Cost Saving (million €)	Total Cost Saving (%)
100	1068.91	6084.96	7153.87	6.09
90	5247.53	2282.59	7530.12	6.38
80	5379.22	2331.2	7710.43	6.52
70	5567.2	2349.78	7916.98	6.67
60	5682.48	2457.27	8139.75	6.83
50	5805.74	2586.18	8391.93	7.00
40	6026.92	2653.06	8679.98	7.19
30	6108.06	2877.51	8985.57	7.37
20	6078.18	3227.37	9305.55	7.53
10	6279.45	3357.28	9636.73	7.65
0	10901.24	3385.82	14287.06	9.28

and non-domestic meters vary greatly, at €120 and €450, respectively[2], so it is necessary to specify the number of each type of meter. The number of domestic meters should approximate the number of households, which is reported in [10]. The number of non-domestic meters is assumed to be 30% of the number of households.

Based on the data and assumptions above, we estimate the overnight cost of smart meters at €52,247 million (domestic meters account for €24,587 million and non-domestic ones account for €27,660 million) for the 27 countries under consideration in this study. Assuming a rate of return of $r = 0.08$ and a lifespan of smart meters of $T = 50$ year, the annualized cost of smart meters in Europe is calculated as €4,270.8 million (domestic meters amount to €2,009.8 million and non-domestic meters amount to €2,261 million). In contrast, the total cost savings from demand response are estimated at €7,153.87 million or €6,180.06 million if we only consider the residential sector. Moreover, according to [7], 50% to 80% of the cost of smart meters can be recovered through operation benefits, i.e., logistic costs, field operation costs, customer service costs, etc. In conclusion, the benefits of demand response can justify the cost of deploying smart meters.

E. Investment in Low-Voltage Grid

In our capacity expansion model, the objective is to minimize generation capital and generation operating costs, which approximates the long-run equilibrium in a competitive energy market. In this section, we evaluate the impacts of the optimal results from the capacity expansion model on the low-voltage grid.

Generally, residential consumers and small commercial consumers are connected directly to the low-voltage grid. Since the structure of the low-voltage grid is mostly radial, it can be assumed that the cost of distribution line infrastructure is proportional to the peak load. Over-night investment cost (OC) in the low-voltage grid amounts to 862 €/kW in the Netherlands [6], or 8 €/MWh in terms of hourly cost (HC), assuming the same lifespan and rate of return as in the previous subsection. The hourly cost is assumed to be the same in other European countries, and is calculated by the continuous discounting formula:

$$HC = \frac{r \cdot OC}{1 - 1/(1+r)^T} * 1000/8760. \qquad (7)$$

As we cannot distinguish the consumption profile of residential and small commercial consumers from the total consumption profile in the data[3], we compare the difference of system peak load under inelastic demand and demand response when only residential consumers are mobilized. Then the difference of investment cost is estimated according the difference of system peak load.

According to our study, by mobilizing residential demand response, the system peak could increase. On the whole, this causes increased investment cost in the low-voltage grid by €8180.7 million, which exceeds the generation capital and operating cost saving (€6,180.06 million). The results for each country are described in figure 5. In some countries, demand response still has positive impacts, but in others, especially Germany, Italy and Spain, the impacts are remarkably negative. The increased peak load in the low-voltage grid mainly arises from two aspects. Firstly, flexible consumers are shifted to periods when renewable supply is abundant, assuming that renewable supply is centralized rather than behind the meter. This results in a peaking of distribution level demand. Secondly, supply to flexible consumers is not coordinated. In Fig. 6, Germany is used as examples to explain the two reasons.

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[2] According to a more recent report [4], the costs of domestic smart meters, including installation costs, meter asses costs and Home Area Network costs, are estimated to be £120.

[3] Synthetic load profiles, which represent the typical profiles of different types of consumers, are available for some countries, but we are not able to find the data for all European countries

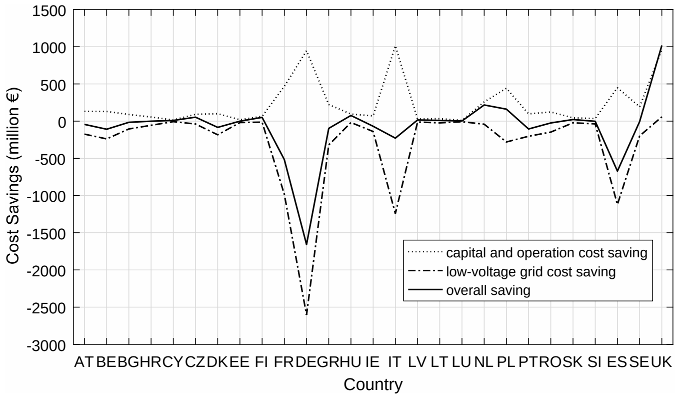

Fig. 5. Cost savings in each country. Capital and operation cost savings are always positive, but low-voltage grid cost savings could be negative in some countries.

This observation indicates that when mobilizing demand response, it is necessary to account for distribution system infrastructure upgrades. This arises from the fact that renewable supply can cause residential demand peaks.

IV. CONCLUSIONS

In this paper, we carry out a long-run cost-benefit analysis of demand response for the European system. The results show significant cost savings by implementing demand response, most of which is achieved by mobilizing residential consumers. Moreover, investment costs in smart meters can be justified from the perspective of energy suppliers. There are three directions that we plan to consider in future research. Firstly, we wish to include hydro resources in the model and then re-evaluate the benefits of demand response. Secondly, we are interested in developing a more realistic model for residential consumers and conducting the analysis with a focus on the residential sector. Additionally, it is worthwhile to perform the analysis from the system perspective, with a more careful modeling of the role of DSOs.

One notable finding from this study is that there exists significant cost saving potential in the residential sector. However, this observation is grounded on the assumption that all the flexible energy in the residential sector can be effectively mobilized. Also, costs of distribution system infrastructure upgrades need to be taken into consideration when mobilizing residential demand response.

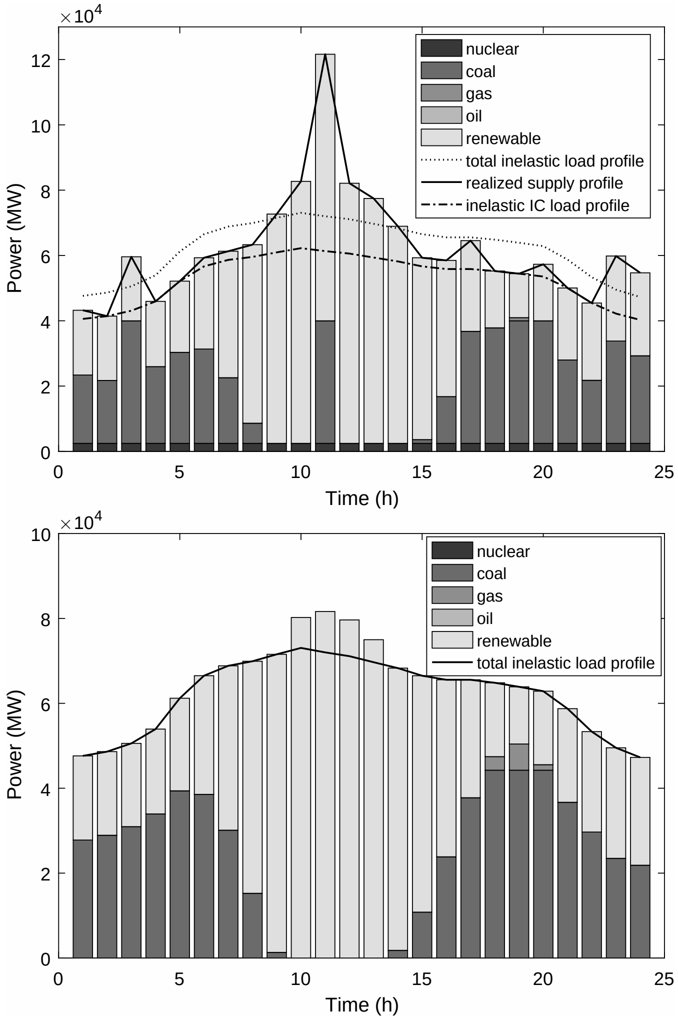

Fig. 6. Supply and consumption profiles of Germany in the day with peak demand under demand response. In the upper panel, bars in different gray scales describe the production from different technologies, i.e., nuclear, coal, gas and renewable. The dotted curve shows total inelastic load profile, while the solid curve shows the realized supply profile when the flexibility of residential consumers is mobilized. The dash-dotted curve illustrates the inelastic industrial and commercial load profile. The peak load appears in hour 11, but this can be reduced by shifting some flexible consumers to other hours without increasing operating cost. The lower panel shows the same day with all sectors being inelastic (nuclear is not invested in under this policy). In this case renewable production is curtailed during hour 10 to 13.

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