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Distributed energy storage aggregation, quantitative evaluation of replicability and scalability

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Abstract— The paper presents the results of a study on replicability and scalability carried out within the SENSIBLE project. In this study a simplified methodology for simulating the behaviour of a market based distributed energy storages coordination has been implemented. Attention has been paid to capture the core of the problems without falling into excessive details of the different solutions (centralised, decentralised) developed. After this, data have been gathered or simulated for a large number of necessary datasets, including electricity consumption in different neighbours, electricity wholesale and retail prices, in six European countries. Central to this stage has been the use of BUS (Bottom Up Simulator) a load profiles simulator developed at MINES ParisTech which has been used to simulate load curves in the different European countries considering historical local weather conditions.

Index Terms—Energy storage, Batteries, Power system management

I. INTRODUCTION

Scalability and replicability are relevant concepts for the evaluation of the benefits of innovative solutions. The attention on these concepts is especially high in R&D projects, where solutions are developed and tested in limited demonstrators. In order to understand the potential of the solutions tested, an evaluation of their performance in other conditions is therefore necessary, but extremely difficult due to the complex nature of the problem. According to [1] both problems can be seen as the result of the interaction of four quite diverse factors: 1) technical, 2) economic, 3) regulatory and 4) acceptance. For this reason evaluations of replicability and scalability have been conducted through surveys or discussions with experts such as in [1], [2] and [3].

The objective of this study is to describe the potential of the solutions developed in SENSIBLE [4] in other contexts (replicability) and with higher DES penetration rates (scalability). As mentioned above the approach followed for this work can be divided in two steps: 1) first a simplified model of a use case has been defined, 2) then scenarios of residential consumption and PV production are generated. This corresponds to using two of the factors mentioned above: technical and economic.

II. METHODOLOGY

This chapter describes these two actions, the data used as inputs and the methodology used to carry out a sensitivity analysis.

A. Technical-economic problem model

For this stage, it has been decided to focus on developing a model able to capture the insights of the process and needing limited data in order to facilitate the scalability and replicability simulations. The model is then built on top of the following assumptions:

- The presence of several flexibility resources aggregated at the distribution level. In the project DES are coordinated through a centralised (Evora demonstrator) or decentralised (Nottingham demonstrator) approach. This simulation won't try to replicate the inner mechanisms of these two approaches but will rely on the assumption that DES in a neighbourhood will be able to react to a specific order.
- The presence of several network users requesting flexibility. The solutions developed allow DES to answer to multiple solicitations, creating value for residential users, network operators and retailers.
- The flexibility provided is rewarded through different schemes. Key for the development of DES are the business models conceived necessary to propose DES services to potential users and to finance the DES. Also, in this case, it has been chosen not to model in detail each business model, but to consider a success rate of the business model to allow the service to be provided and a compensation to be received.
- No hypothesis is made on the technology behind storage such as water heaters or Li-ion batteries. These are two different flexibility sources with different costs and furthermore their relative cost is expected to change considerably in the following years, mainly because of Li-ion batteries cost reduction. For this reason, a simpler model describing a generic storage has been conceived.

The modelling of the different aspects of the problem is described below

1) Flexibility demand from DSO

Regarding this parameter it is necessary to simulate the frequency and the size of flexibility calls from the DSO, it is also necessary to estimate a reasonable value associated to the answer of this call. The following approach is used: a flexibility requests is issued when the load in the neighbourhood at time t ($W_{l,t}$) exceeds the rating of the transformer (R_{tr}). The size of the flexibility request ($FW_{l,t}$) is equal to the difference between the load and the transformer rating when this is positive, as shown in (1). The value of the flexibility ($FE_{l,t}$) requested is modelled taking inspiration from the penalties applied to the breaching of the contractual power in the French regulation: the penalty is roughly 10 times the average market value of electricity (Pe,y) as shown in (2). The negative value of the flexibility indicates that the power is expected to be discharged from the battery.

$$FW_{l,t} = -\max(0 ; W_{l,t} - R_{tr}) \quad (1)$$

$$FE_{l,t} = 10 * Pe,y \cdot FW_{l,t} \quad (2)$$

2) Flexibility demand from PV plants

In order to estimate the frequency and size of local PV producers' flexibility requests and to estimate their value the following approach has been chosen. It has been assumed that PV producers must curtail their production in order ($FW_{pv,t}$) to prevent reverse power flow from the transformer, so when the difference between the PV production ($W_{pv,t}$) and load consumption is greater than zero, as shown in (3). This is equivalent to a situation where local production must be consumed locally or when network issues at higher voltage prevent further injection of power. The value of the flexibility request from PV ($FE_{pv,t}$) is considered equal to the levelized cost of energy (LCOE) produced by the PV as shown in (4). The positive sign means that the power will be consumed by the battery.

$$FW_{pv,t} = \max(0 ; W_{pv,t} - W_{l,t}) \quad (3)$$

$$FE_{pv,t} = LCOE * FW_{pv,t} \quad (4)$$

3) Flexibility demand from electricity price arbitrage

In this case it is expected that the storage will receive a flexibility request to charge ($FW_{e,t}$) equal to the maximum available capacity if electricity prices are at the lowest value of the next 24 hours, where the maximum capacity is the maximum between the energy ($R_{b,e}$) and the power ($R_{b,w}$) rating of the storage, as explained in (5). At the same way, the flexibility request will be negative if the electricity price is the highest in the next 24 hours. The value of this flexibility request due to price arbitrage ($FE_{e,t}$) is equivalent to the difference between the electricity price at time t (Pe,t) and the average of the electricity price in the following 24 hours ($Pe,24h$), as shown in (6).

$$FW_{e,t} = \begin{cases} + \max(R_{b,w} ; R_{b,e}) & \text{if } Pe,t = \min(Pe,day) \\ - \max(R_{b,w} ; R_{b,e}) & \text{if } Pe,t = \max(Pe,day) \end{cases} \quad (5)$$

$$Pe,day = Pe,t, Pe,t+1, \dots Pe,t+24 \quad (5.1)$$

$$FE_{e,t} = FW_{e,t} * (P_{e,24h} - P_{e,t}) \quad (6)$$

4) Storage modelling

A storage is defined by several parameters, notably its power rating ($R_{b,w}$), corresponding to the maximum power that can be consumed or injected in the network, the energy rating ($R_{b,e}$) corresponding to the maximum amount of energy that can be stored and the cost associated to the flexibility activation ($FE_{b,t}$) taking into account aging and losses. At every time step the battery cannot charge ($FW_{b,max,t}$) more than its power rating or more than the available storage capacity, equivalent to the difference between the rated energy and the energy stored at time t ($E_{b,t}$), as shown in (7). Also, it cannot discharge ($FW_{b,max,t}$) more than its rated power and more than the amount of energy stored at time t , as shown in (8). In both equations the term dt indicates the length of the time step and the power is considered positive if charged into the battery, negative otherwise. It is also expected the storage to discharge

$$FW_{maxb,t} = \max(R_{b,w} ; (R_{b,e} - E_{b,t})/dt) \quad (7)$$

$$FW_{b,max,t} = -\max(R_{b,w} ; E_{b,t}/dt) \quad (8)$$

5) Storage charge and discharge

The storage is charged and discharged according to economic principles: if revenue from selling the flexibility is greater than its cost, then the offer is accepted and the storage charged or discharged of the amount requested according to its technical constraints of power and energy. Otherwise the offer is not accepted. In order to take into account the efficiency of the business models, a coefficient ranging X_{bm} from 0% to 100% is used to capture the fact that the storage can be paid less than the total value of the flexibility request (eg: 50%).

The approach can be summarised with the following algorithm:

Step 1: find the offer with the maximum revenue ($FW_{max,t}$; $FE_{max,t}$) among ($FW_{l,t}$; $FE_{l,t}$), ($FW_{pv,t}$; $FE_{pv,t}$), ($FW_{e,t}$; $FE_{e,t}$)

Step 2.1: if $FE_{max,t}/\text{abs}(FW_{max,t}) > X_{bm} * FE_{e,t}$ then the offer is accepted and go to Step 2.2

Step 2.2: $FW_{b,t} = \min(FW_{maxb,t}, FW_{max,t})$

In the time steps when the storage does not accept offers it charges or discharges itself with the aim at reaching a charge of 50% in a horizon of 24h. This simple rule is implemented in order to prevent the battery from being completely full or completely empty and being unable to accept offers; it has been tested that although being not optimal regarding the purchase time of electricity, it allows increasing the number of cycles and the yearly turnover of the storage). In this phase, when it is charging will pay the electricity at the wholesale market price ($P_{e,t}$) plus a network charge (P_{en}), as shown in (9). When it discharges the electricity is sold to local loads at a fraction (depending on X_{bt}) of the difference between the retail electricity price (P_{er}) and the network charges, as shown in (10). The network charge is calculated as the difference between the retail price of electricity (P_{er}) in the country, minus the average yearly wholesale cost of energy ($P_{e,y}$) as shown in (11). The retail cost of electricity has been previously corrected to remove the VAT.

$$P_{e,buy,b,t} = P_{e,t} + P_{en} \quad (9)$$

$$P_{e,sell,b,t} = (P_{er} - P_{en}) * (1 - X_{bm}) + P_{en} \quad (10)$$

$$P_{en} = P_{er} - P_{e,y} \quad (11)$$

B. Scenarios generation

Central to this study is the realisation of coherent time series for electric demand and photovoltaic production representative of different neighbourhoods in different European countries.

For this it has been used BUS (Bottom Up Simulator) [5] a load modelling tool developed at MINES ParisTech and able to simulate individual or aggregated electric load time series taking into account a large number of parameters regarding the load characteristics (use, surface, age of the building...) and weather conditions (such as temperature, solar radiation, rainfall). The tool is able also to create profiles for renewable production such as PV generation, again taking into account plants characteristics and historical weather conditions. This allows creating correlated time series of renewable production and electric consumption in the same location. For this the tool makes use of historical weather reanalysis from NASA's MERRA model [6].

For this study a total of 540 scenarios for electric demand and 180 for PV production have been simulated. Each scenario is made of a time series of 8760 hourly time steps of the electric consumption or production in kWh. Consumption scenarios are relative to a group of users (LV loads connected to a distribution transformer) and PV are relative to a single power plant.

Load scenarios are representative of: 1) Thirty residential neighbourhood, 2) For three network types: rural, suburban and urban, 3) In six countries: DE, ES, FI, FR, PT, UK. PV scenarios are relative to: 1) Thirty power plants, 2) In the six countries mentioned.

A key parameter of the scenarios is the value of the load and the PV production respect to the transformer rating. For this in each scenario the load is made dimensionless and scaled so that its maximum value is equal to the 110% of the transformer rating. The same is made for the PV plant. For each country, a sensibility analysis is made for one neighbourhood of the rural network where this and other parameters are modified in order to understand the sensitivity of the results. This is described with more details below.

C. Sensitivity analysis

As mentioned above, a sensibility study has been carried out in order to determine the relative importance of several parameters used in the model and in order to provide insights of the different outcomes of the simulation in case the value used are considered arbitrary or far from expectations. A list of the parameters object of the sensitivity study and the range assumed by their values is reported below.

Load peak power respect to transformer rating ($W_{l,max}/Rtr$): three values are tested for this parameter: 110%, 120% and 130%.

PV peak power respect to transformer rating ($W_{pv,max}/Rtr$): three values are tested for this parameter: 110%, 120% and 130%.

Battery energy rating ($R_{b,e}$): three values are tested for this value: 10%, 20% and 30% in kWh of the transformer rating. The value is expressed in kWh.

Battery power rating ($R_{b,w}$): three values are tested for this value: 10%, 20% and 30% of the transformer rating. The value is expressed in kWh.

Storage charge and discharge cost (FE_c): Five values are tested for this parameter: 0.01, 0.05, 0.1, 0.15, 0.2 E/kWh.

Business model profit rate (X_{bm}): four values are used for this parameter: 25%, 50%, 75% and 100%. The last value must be intended as a method to understand what is the technical maximum that can be obtained with the use of storage.

The sensitivity analysis explores all the permutations among these parameters for a total of 1620 cases. The sensitivity analysis is performed only once per country for the first neighbourhood of the rural network.

III. DATA

A. Weather

For the six countries a single location has been used to retrieve weather data relative to the year 2016: the city of the SENSIBLE partner in that country or the city of the demonstrators, as seen in TABLE II. For each location hourly time series are derived for the following parameters: 1) Solar radiation, 2) Air temperature.

B. PV plants

The thirty PV plants are not defined by their technology but only by their orientation and tilt, which has been made to range from 170 to 190 degrees north and from 33 to 57 degrees respect to the horizon. The resulting time series per each plant and per each site has been made dimensionless, in order to be scaled according to the needs of the simulation.

C. Residential load

In order to generate load scenarios, A large number of information regarding each user and each building is necessary for the BUS tool mentioned above. Considering the difficulty in obtaining these data in many occasions, the tool is able to estimate them from a minimum set of values (namely use category and building surface). In this study this feature has been used and a large number of loads have been generated starting from the basic information provided by the tables TABLE II.

D. PV LCOE

The LCOE for residential PV systems is dependent from the site irradiation but also from the country labour cost. A coherent estimation for the six countries included in this study has been found in [7] and is reported in TABLE II. .

E. Electricity prices

Another key parameter of the study is the retail cost of electricity. This information is easily available for all countries considered and for coherence has been taken from [7] the same source used for PV LCOE.

TABLE I. REPARTITION OF DIFFERENT FEATURES IN THE THREE NETWORKS CONSIDERED.

Type	Rural	Suburb.	Urban	Electric heating	Heat pump	Air conditioning
House	30%	60%	2%	30%	0%	10%
Apartment	30%	20%	45%	50%	0%	20%
Office	15%	10%	30%	50%	0%	90%
Shop without cold	5%	3%	5%	75%	75%	100%
Shop with cold	5%	3%	5%	75%	75%	100%
Hotel	3%	1%	1%	50%	50%	100%
Restaurant	5%	1%	5%	50%	50%	100%
Café/bar	5%	1%	5%	50%	50%	100%
Teac./ research	2%	1%	2%	50%	50%	100%
EV charging stat.	0%	0%	0%	50%	50%	100%

TABLE II. SUMMARY OF RELEVANT DATA USED FOR THE DIFFERENT LOCATIONS.

Country	City	Lat	Long	LCOE [E/kWh]	Retail electricity cost [E/kWh]
Germany	Nuremberg	49.43	10.99	0.15	0.292
Spain	Sevilla	37.38	-5.99	0,1	0.227
Finland	Helsinki	60.10	24.73	0.2	0.156
France	Nice	43.69	,7.253	0.12	0.159
Portugal	Evora	38.574	-7.91	0,1	0.213
UK	Nottingham	52.95	-1.24	0.17	0.180

IV. RESULTS

Simulation results are reported here in a series of tables. In order to read the results, it is necessary to understand the logic behind their representation, for example: what is a correct metrics for replicability, or for scalability? And what is a correct metrics for DES impact?

Regarding the metrics for replicability, it has been easy to report results' breakdown by country, as the model used takes into account both climatic and energy cost aspects.

Regarding scalability the problem is more complex. Firstly, storage is characterised by energy and power rating. It was expected the energy rating do be more relevant than the power rating, and this is proven in the tables Table 5. This comparison allowed to simplify results reporting by showing simply the dependence on energy rating and to consider this parameter as a proxy for scalability. But a second more subtle issue must be captured: the actual usage of the storage depends not only on its size, but also on its relative cost respect to the flexibility needs of the other network users, therefore storage activation cost has an impact far higher than storage size and its value must be taken into account.

Finally, two metrics have been used to quantify DES impact. From a technical point of view, it has been chosen to represent the ratio of the storage activations on the total flexibility requests. Also, it has been chosen to report the average profit per year and per storage unit.

A first analysis shows the relative importance of the energy rating on the power rating of the battery: both metrics are linearly sensitive to the energy rating but they do not show any dependence on power rating. This means that storage activations correspond to a large number of relatively small sizes of power but often correlated. Results are presented in TABLE III.

TABLE III. IMPACT OF ENERGY AND POWER RATING. (A) AVERAGE OF THE RATIO BETWEEN FLEXIBILITY ACTIVATIONS AND CALLS, VALUES IN %, (B) AVERAGE STORAGE PROFIT, VALUES IN E/KWH/YEAR

		Energy rating		
		0,1	0,2	0,3
Powerrating (a)	0,1	9,2	10,78	12,17
	0,2	9,18	10,14	11,76
	0,3	9,16	10,12	11,42
Power rating (b)	0,1	9,59	8,35	7,47
	0,2	9,59	8,65	7,93
	0,3	9,59	8,65	8,1

A second analysis is reported in TABLE IV. TABLE V. where the two metrics for DES impact are reported for each country, each network type and each storage energy rating respect to the transformer. The breakdown of the results by country and by network type helps to visualise the importance of several aspects of the problem, such as wholesale and retail electricity prices, PV LCOE, load and PV production profiles.

TABLE IV. AVERAGE OF THE RATIO BETWEEN FLEXIBILITY ACTIVATIONS AND CALLS, BREAKDOWN BY COUNTRY AND SENSITIVITY ANALYSIS ON STORAGE SIZE VALUES IN %

Energy rating	Network	Country					
		DE	ES	FI	FR	PT	UK
10%	RU	14,16	9,68	8,46	7,07	0,86	8,88
	SU	13,36	9,24	8,77	7,03	7,45	10,02
	UR	13,59	10,12	8,76	8,01	10,16	9,67
20%	RU	15,93	10,76	9,55	8,07	0,86	9,85
	SU	14,93	10,44	9,57	8,01	8,39	11,13
	UR	15,12	11,73	9,88	9,24	11,82	10,95
30%	RU	17,88	15,96	10,61	9,07	0,86	10,95
	SU	16,77	11,74	10,41	8,95	9,41	12,35
	UR	16,83	13,33	11,00	10,36	13,37	12,22

TABLE V. AVERAGE STORAGE PROFIT, BREAKDOWN BY COUNTRY AND SENSITIVITY ANALYSIS ON STORAGE SIZE VALUES IN E/KWH/YEAR

Energy rating	Network	Country					
		DE	ES	FI	FR	PT	UK
10%	RU	17,69	13,41	4,99	7,74	1,59	5,96
	SU	13,39	9,66	5,86	6,95	9,36	7,94
	UR	14,65	11,80	6,94	8,91	18,06	7,78
20%	RU	15,39	11,72	4,49	6,98	1,59	5,48
	SU	12,26	8,88	5,11	6,29	8,55	7,27
	UR	13,00	10,59	6,08	7,75	15,39	7,10
30%	RU	14,00	11,06	4,13	6,32	1,59	5,07
	SU	11,41	8,30	4,57	5,75	7,94	6,68
	UR	11,80	9,78	5,48	6,90	13,77	6,49

A singular case is represented by Portugal, a country where it is observed both the lowest and the highest distributed energy storage profitability respectively in the rural and urban network. This observation confirms the

interest in studying this solution in the Portuguese network as it is possible to find situations where DES can offer tangible benefits. The analysis shows also that the German network places itself as the most profitable location for DES, whilst the UK is the less interesting. The reason of this must be found in the higher residential electricity prices in Germany and probably also in the highest solar potential.

Finally, a last analysis has been carried out by reporting the two metrics for DES impact for each country and each storage activation cost. This is reported in TABLE VI. and TABLE VII.

As expected the profit generated by the DES decreases with the increase of its activation cost. This is because of two reasons: firstly, a higher cost corresponds to lower profits and secondly because higher battery activation costs reduce the number of occasions when it is profitable for DES to be activated.

The effect of DES activation cost is evident also on the share of calls that DES answer. The table is characterised by a series of plateaux and they can be interpreted as the different markets where DES can be competitive. For example, in this modelling the highest paying service is represented by peak shifting by DSO whilst the lowest paying is represented by day/night price arbitrage for customers, according to the relative activation cost DES can or cannot answer these calls and this determine its daily usage.

TABLE VI. AVERAGE OF THE RATIO BETWEEN FLEXIBILITY ACTIVATIONS AND CALLS, BREAKDOWN BY COUNTRY AND SENSITIVITY ON STORAGE ACTIVATION COST, VALUES IN %

		Country					
		<i>DE</i>	<i>ES</i>	<i>FI</i>	<i>FR</i>	<i>PT</i>	<i>UK</i>
Storage Activation cost [E/kWh]	<i>0,01</i>	24,65	18,21	22,53	23,80	13,42	27,21
	<i>0,05</i>	13,03	11,80	11,17	13,22	8,93	11,93
	<i>0,10</i>	13,00	11,80	10,90	1,77	8,93	11,63
	<i>0,15</i>	12,97	11,80	1,87	1,74	1,91	1,22
	<i>0,20</i>	12,97	1,26	1,87	1,68	1,91	1,22

TABLE VII. AVERAGE STORAGE PROFIT, BREAKDOWN BY COUNTRY AND SENSITIVITY ON STORAGE ACTIVATION COST, VALUES IN E/kWh/YEAR

		Country					
		<i>DE</i>	<i>ES</i>	<i>FI</i>	<i>FR</i>	<i>PT</i>	<i>UK</i>
Storage Activation cost [E/kWh]	<i>0,01</i>	28,43	23,41	12,74	16,88	17,11	17,05
	<i>0,05</i>	16,98	13,83	6,29	8,32	10,58	7,79
	<i>0,10</i>	13,13	8,60	2,54	3,83	7,00	3,74
	<i>0,15</i>	7,46	3,38	2,55	3,25	4,19	2,45
	<i>0,20</i>	2,77	2,76	2,04	2,74	3,65	2,06

V. CONCLUSIONS

The report presents the results of the study on replicability and scalability for the market based optimal management of distributed energy storages.

In this study a simplified methodology for simulating the behaviour of the solutions developed in the SENSIBLE project has been implemented. Attention has been paid to capture the core of the problems without falling into excessive details of the different solutions (centralised, decentralised) developed.

After this, data have been gathered or simulated for a large number of loads corresponding to different neighbours in rural, suburban and urban networks in the six countries part of the project.

Finally, the results of the simulation, made in large part by a sensitivity analysis, have been gathered and analysed. The main results can be summarised as follows:

- DES performance in terms of utility for other network users and profit generated grows linearly with the storage energy sizing but is relatively indifferent to storage power sizing. This means that most of the flexibility requests are made of little power calls but often repeated in time.

- The highest use and profitability for DES has been found in Germany, probably because of the higher electricity retail cost. The most variable results have been observed in Portugal between rural and urban networks.

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