# ENERGY STORAGE AND ENERGY MANAGEMENT IN DISTRIBUTION GRIDS, COMMUNITIES AND BUILDINGS: RESULTS FROM SENSIBLE, A FLAGSHIP PROJECT

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## ABSTRACT

*In a time of energy transition, this article summarizes the most relevant conclusions obtained from the SENSIBLE project [3], which aimed to demonstrate that the 2030 EU energy policy targets are achievable, and that distributed energy storage has a crucial role enabling such ambitious targets. SENSIBLE developed innovative features and functionalities based on energy storage and energy management. It was elected as an EU flagship innovation project for its innovation, excellence and ambitious targets of applying several use cases to three real world domains: i) distribution grids; ii) customers and iii) buildings. Grid domain developments were demonstrated in Évora as well as new energy services provision to end users, whilst the Nottingham demonstrator addressed the energy community domain. In Nuremberg, storage applications in the building domain were demonstrated. SENSIBLE's results show that energy storage applications are a key tool to enable the flexibility required for the energy transition and can provide benefits to the grid as well as the end user. The project's conclusions from the three domains, which are underpinned by the KPI results, prove the impact of energy storage on the energy system of the future.*

## PROJECT GOALS AND SCOPE

The EU's 2030 climate and energy framework [1], recently reinforced by the Winter Package directive [2], has defined ambitious targets for EU countries to achieve more competitive, secure and sustainable energy systems. The framework promotes a low-carbon economy, a central role of the customer within the energy transition as well as the importance of an integrated EU energy market.

In a time where the energy paradigm is changing, with renewables replacing fuel-based power generation and consumers playing a more active role in the decarbonization, uncertainty and unpredictability of the generation and a more volatile consumption brings new technical challenges for the energy system. Flexibility, energy storage and energy management technics built on top of smart-grid technologies are unavoidable elements towards a more secure, reliable, safe and cost-effective energy system for all EU citizens. SENSIBLE was conceived under this context aiming at integrating small-scale storage technologies, together with Renewable Energy Sources (RES), into the distribution grid, communities and buildings. The developments of the project were demonstrated in Évora/Valverde (Portugal), Nottingham (UK) and Nuremberg (Germany). The project run from January 2015 to December 2018 and had an overall budget of 15M €. It was led by Siemens AG, with EDP Labelec heading the demonstration work package. More information can be found in [3].

| | ID | SENSIBLE HIGH LEVEL KPI | Évora | Nott | Nur |
|---|---|---|---|---|---|
| EEGI Specific KPI | 1 | Increased RES and DER hosting capacity | X | | |
| | 2 | Reduced energy curtailment of RES and DER | X | | X |
| | 3 | Power quality and quality of supply | X | X | |
| | 4 | Increased flexibility from energy players | X | | X |
| Project's Goals | 5 | Investment deferral | X | | |
| | 6 | Increased self-consumption | X | X | X |
| | 7 | Increased socio-economic welfare | | X | X |
| | 8 | Consumer awareness and engagement | X | X | |
| | 9 | Losses minimization (network, inverters) | X | | |

Figure 1 - List of SENSIBLE KPIs

SENSIBLE's ultimate goal was to create integrated value for several energy stakeholders, like the Distribution System Operator (DSO), market players and end-users, supported by competitive flexibility-based business models at the individual and aggregated level. SENSIBLE KPIs, shown in Figure 1, were closely linked to European Electricity Grid Initiative goals and were then broken down into low level KPIs, which measured the metrics of the project as shared in this article.

## DEMONSTRATION

The Real Time Platform (RTP) (developed by Indra[1]), which was common to the three demonstrators, played an important role bridging the gap between the different architectural layers. For the equipment/site ICT layer, smart-grid/community/building components were developed to physically integrate with the energy storage

[1] *All companies mentioned in this section are SENSIBLE project partners*

systems (ESS). At the tools layer, advanced management and optimization software was developed to control the ESS and other Distributed Energy Resources (DER) according to their roles in the related Use Cases (UC). The RTP integrated these layers to the demonstrator's specific requirements, which included grid operation tools in the DSO domain (developed by Inesc and Indra), generation and load forecast tools (developed by Armines) and a community energy management tool (developed by University of Nottingham) amongst others. Furthermore, the energy market services tool (developed by Empower), which was also common to all three demonstrators, optimized grid/community/building interaction and enabled market participation for the residential and commercial building sector.

Évora demo, shown in Figure 2, was implemented in a rural grid, supplied by a Medium Voltage (MV) overhead line exposed to weather events and with no redundancy. The focus was to demonstrate storage-enabled functionalities improving power quality and grid resilience/robustness in distribution grids as well as to enable new energy services to end users based on smart-grid functionalities of INOVGRID [4]. All 240 customers of the demonstrator were part of EDP Distribuição's (EDPD) smart-grid infrastructure. Battery ESS, from 10 kW up to 480 kW, were installed as grid assets both at MV [4] and Low Voltage (LV) provided by EDP Labelec and GPTech, and operated by EDPD as DSO, with grid forming and islanding capabilities at both voltage levels. A secondary substation switchgear with islanding capabilities and advanced protection and automation mechanisms was demonstrated. At the residential side, PV, 3.3 kWh batteries, water heaters, smart plugs and Home Energy Management Systems (HEMS) were installed in 25 customer households and integrated with energy markets. [5] gives complementary information on micro-grid operation works and tests, which took place in the Évora demonstrator.

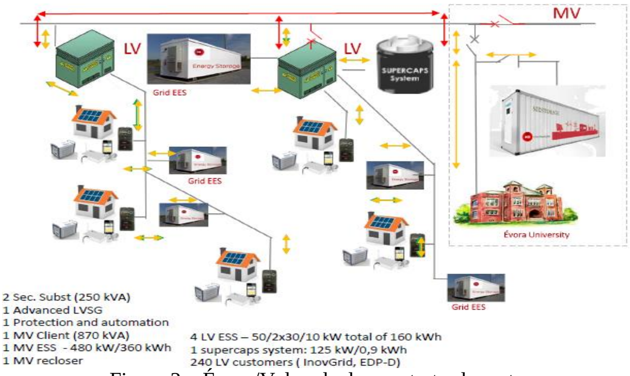


Figure 2 – Évora/Valverde demonstrator layout

The market connectivity in the Évora demonstrator provided the flexibility and demand-side management capability in the retail market context, which enabled the utilization of distributed ESS for the combined benefit of a retailer and the distribution network. The forecasted flexibility can be purchased by a retailer and used for optimizing its portfolio. Similarly, in case of congestions, the DSO can purchase flexibility.

The Nottingham demonstrator was implemented in an inner-city neighborhood, called the Meadows, with a high level of environmental commitment. It focused on storage-enabled energy management and community driven energy strategies. The associated UCs aimed to manage PV generation more effectively using ESS. The purpose of all three UCs was to demonstrate technical and financial benefits to the individual end user or a community based Energy Service Company (ESCO), e.g. by increasing PV penetration on a building or communal level. Participants in the deprived Meadows area were recruited, some of whom already had existing PV systems, to receive commercial energy storage equipment and monitoring equipment developed by the SENSIBLE project. 27 households received 6.4 kWh batteries, water heaters or monitoring equipment only. Two community buildings with existing PV systems, i.e. a school and a library, also received 13.5 kWh battery systems. The market processes of the Nottingham demonstrator could be used to support the formation of an independent energy community by providing information on available flexibility within the communal grid and the capacity to enhance self-consumption of locally generated energy.

The Nuremberg demonstrator linked the Nuremberg University and Siemens AG laboratory in Erlangen. It is focused on energy storage integration in larger buildings, involving batteries, thermal storages, and different generators, such as combined heat and power units and heat pumps for different energy vectors (electricity, heat, gas). The Nuremberg demo addresses three UCs. The developed Building Energy Management System (BEMS) first aims to operate the building infrastructure in such a way to minimize the energy obtained from power grids by utilizing locally generated power efficiently. For that purpose, the BEMS maximizes the self-consumption of locally generated electrical/thermal energy. Furthermore, onsite energy conversion and storage units (e.g. electro-chemical and thermal storage) are jointly optimized across energy vectors (thermal and electrical) to maximize energy efficiency when operating the entire infrastructure of the building. As a result, the energy demand (both electrical and thermal) obtained from external providers are reduced. The interfaces between an energy supplier and building energy management systems were defined, in order to enhance procurement processes and to increase the utilization of the flexibility. Furthermore, the defined processes enable exchange of forecasts from buildings supporting the supplier's energy procurement.

The approach allows to send/negotiate a 15 min. resolution nominal building load profile to the energy supplier, DSO, or other party, day-ahead of energy consumption. The market platform also gets day-ahead information on the flexibility, the building can provide. At time of energy consumption, the multi-energy-vector BEMS optimizes the operation of the storage and generation infrastructure. By using the remaining flexibility, it can also stick to the forecasted load profile. The building operator is rewarded for providing this flexibility as usual for today's balancing power markets. In the future, it's expected that even smaller commercial buildings or stakeholders can participate in such schemes.

## RESULTS AND KPI CALCULATION

Figure 3 lists the UC demonstrated by domain and site, which are explained in this section. In Évora, UC2 demonstrated several benefits that customers may get if additional energy services were to be provided, from self-consumption over management of contracted power to price arbitrage; all of which result in energy bill reductions. Figure 4 shows the stacking of such values for a specific LV customer in Évora/Valverde. Also 6.5 tonnes of CO2 emissions were avoided during the last two years of demonstration, due to the local PV generation. UC8 showed that MV ESS can be a powerful asset for the DSO to optimize the MV network operation, when correctly sized, well located and exploited with reliable forecasts. UC9 demonstrated that only in some cases voltage profile can be improved, mainly due to the limitation of LV storage devices withstanding unbalanced operation, but that grid technical losses were decreased**.**

| #UC | Use case short name | Demo | Domain |
|---|---|---|---|
| 1 | Managing building energy flexibility | Nuremberg | Buildings |
| 2 | Flexibility valuation in energy markets | Évora | Customers |
| 3 | Increased percentage of self-consumption | Nuremberg | Buildings |
| 4 | Optimized energy procurement | Nuremberg | Buildings |
| 5 | Microgrid PV Management | Nottingham | Grid/Customer |
| 6 | Enabling an independent energy community | Nottingham | Customers |
| 7 | Microgrid Energy Market | Nottingham | Grid/Customer |
| 8 | Optimizing the MV Distribution Network | Évora | Grid |
| 8a | Extented islanding Use case | Évora | Grid |
| 9 | Optimizing the operation of storage in the LV grid | Évora | Grid |
| 10 | Islanding Operation of Low Voltage Networks | Évora | Grid |
| 11 | Microgrid Emergency Balance Tool | Évora | Grid |

Figure 3 - List of SENSIBLE Use Cases

Demonstration work in Évora showed that the main source of improvement for UC8 and UC9 was associated with an enhancement of the load and generation forecasts.

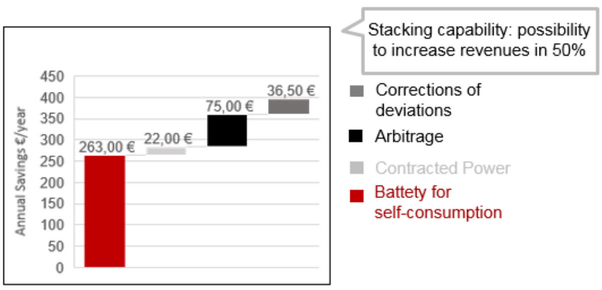


Figure 4: Example stacking of benefits from UC2, for one customer

UC10 proved that unbalanced LV islanding is possible, using distributed automation principles and power electronics, so that the resilience of the grid is increased. UC11 optimized the operation in islanding mode, namely the reserve power and energy that grid forming units could keep in order to withstand the grid. In this case an improvement on reserve power for the LV grid forming units of 89% (21% for energy) was achieved, whilst for the MV grid this value was improved by 29% (14% for energy). Also, in terms of islanding operation duration for the LV network, a maximum operation time of 2h54m is possible, which is 190% compared to Business As Usual (BAU); whilst for MV, a maximum of 1h44m was achieved, which is 103% compared to BAU. In terms of possible faults in MV feeders, 87% of avoided Energy Non Supplied (ENS) could be covered, while 100% of faults affecting the MV client could also be covered. If UC8a was considered, i.e. coordinated LV and MV islanding, see Figure 5, up to 98.9% of ENS could be avoided. References [6] and [7] share additional information about technical results. In Nottingham, lab results for UC5 and UC7 showed that the controller's machine learning particle swarm method can increase PV self-consumption at building level and that charging and discharging patterns can also be optimized based on hourly pricing signals. Both UCs considered the technical constraint of limited export allowance, as is the case in some EU countries. The third UC showed that a well-managed comparatively small battery system, i.e. a 2 kW inverter and 10 kWh battery, can improve a community's power profile at the Point of Common Coupling (PCC) by nullifying it at times, whilst reducing operational costs for an ESCO by shifting energy from high to low priced time periods, as shown in Figure 6.

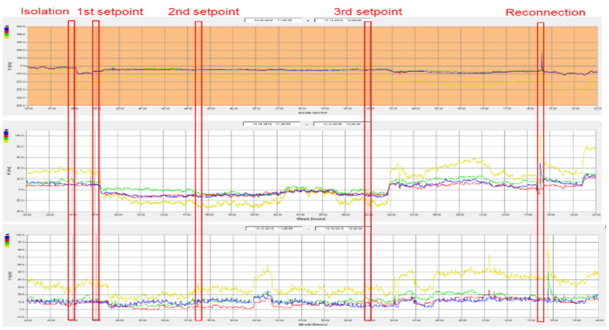


Figure 5: Example of setpoints delivered to energy storage units in extended islanding mode in Évora

On average, the water heaters deployed in the demonstrator raised the self-consumption of the existing PV systems from 52% to 78%, whilst the batteries increased it from 37% to 87%. Furthermore, the batteries increased the self-sufficiency of households with PV on average from 19% to 40%, including the battery system losses. As gas is relatively cheap in the UK, water heaters were only able to achieve average annual savings of 23€. However, PV coupled battery systems yielded average annual savings of 141€ and battery only systems yielded savings of 106€.

The BEMS demonstrated in Nuremberg firstly calculates a day-ahead plan, based on models for each component and the building energy system, load and weather forecasts. During the operation, an online management makes it possible to handle deviations from forecasts or other inaccuracies by doing cyclic re-planning. The two stages are based on a model-driven optimization approach. The objective function, boundary conditions and constraints for the optimization problem are adjusted for the three UCs demonstrated at the Nuremberg demonstrator (Figure 3).

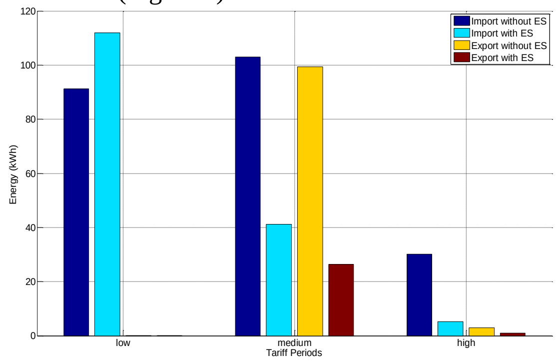


Figure 6: Energy import/export with and without battery storage in relation to variable tariff in Nottingham

This makes it possible to validate a particular UC and see that the BEMS is able to take the intended action. For example, for UC3 ("Increased percentage of self-consumption"), there is an incentive to use self-generated energy (including heat, PV, electricity) to reduce the external energy demand.

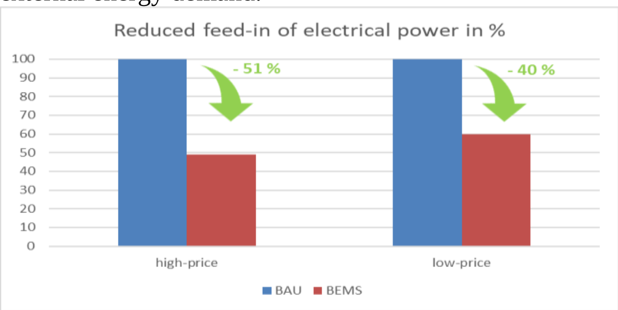


Figure 7: Reduced feed-in of electrical power in %

There are two price-scenarios defined, derived (high/low) from real world energy tariffs ranging from 0.07 to 0.25 Cent/kWh. A peak price component of 100 €/$kW_{peak}$ has been assumed, additionally. All load scenarios are taken from real-world measurement. Each KPI is calculated as the relative difference between SENSIBLE scenario and the BAU scenario. A reduction of power feed-in of 51 % and 40 % respectively ( Figure 7) has been achieved. The self-consumption by has been increased by 8 % and 12 %, respectively (Figure 8).

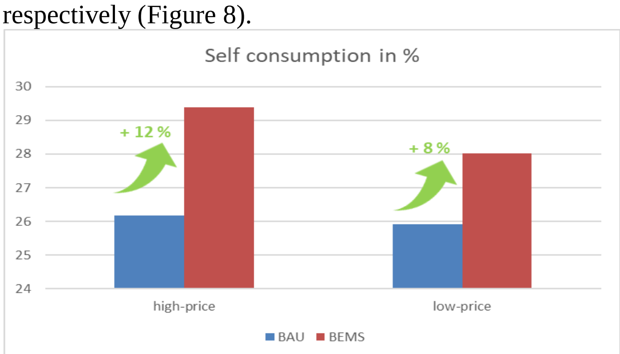


Figure 8: Increased self-consumption for high-price and low-price scenario

Results for UC4 ("optimized energy procurement") show energy cost savings of about 5 %. However, based on our experiences, further reduction (up to 15 %) is achievable by a more advantageous building energy system setup.

The provision of building internal flexibility as balancing power was demonstrated in UC1. Based on the Nuremberg Demonstrator setup, up to 10 % of the system nominal power can be provided as balancing power. Each KPI for a given parameter was calculated as the relative difference between the SENSIBLE scenario and the BAU scenario.

**Increased RES and DER hosting capacity**

The hosting capacity in LV grids KPI could not be calculated, as the installed PV in Évora was not able to reach the technical limitation of the grid; but the hosting capacity in MV networks showed an increase of approximately 25%.

**Reduced energy curtailment of RES and DER**

In Évora, based on the Sequential Monte Carlo Simulation method, it was shown that a reduction of 93% on RES curtailment can be achieved. A futuristic scenario was considered where an additional 50% PV capacity was added and in this case 98% reduction could be achieved by SENSIBLE tools when they operate in order to maximize RES integration. In Nuremberg, the approach is slightly different, where the BEMS is programmed to minimize RES injection in the grid and to increase self-consumption of the building's PV plant. In this case, a 40% of reduction is possible during an off-peak energy price period and 51% during a peak energy price period.

**Power quality and quality of supply**

In Évora a tool based on the Sequential Monte Carlo Simulation method showed that in the MV network the System Average Interruption Frequency Index (SAIFI) can be improved up to 22% and 23% to 24% in the LV grid. In terms of System Average Interruption Duration Index (SAIDI), 28% improvement is achieved in the MV grid and up to 26% in the LV grid.

**Increased flexibility from energy players**

Increased flexibility of energy players, in a case where a retailer uses the flexibility from its customer's portfolio to optimize the participation in energy markets, shows that an increase of 18.74% in power and 59.25% in energy is possible.

**Investment deferral (MV network)**

Considering that storage devices are explored for combined price arbitrage and self-consumption maximization and a 10% limit is used for grid supporting purposes, a 16% to 24% improvement was shown on investment deferral when compared with the BAU scenario.

**Increased percentage of self-consumption**

In Évora up to 67% of the self-consumption was achieved during demonstration and approximately 26% of those were due to the storage devices. Also, the HEMS played a crucial role managing both storage and flexible loads. In Nottingham, water heaters raised the self-consumption from 52% to 78%, whist the batteries increased it from 37% to 87%. In Nuremberg this KPI was a bit lower, with a 12% increase during peak energy prices and an 8%

increase during low energy prices.

**Increased socio-economic welfare**
In Évora an improvement on socio-economic welfare of 27% was achieved (equating on average to 25€/month), whilst in Nottingham a very similar 28% was achieved. In Nuremberg, where buildings are the "customer", up to 15% improvement was possible.

**Consumer awareness and engagement**
In Évora the acceptance and engagement of customers reached a level of 93%, whilst in Nottingham it was 82% for residential participants and 67% for public and private participants.

**Losses minimization (network, inverters)**
In Évora the technical losses reduction in the LV grid reached 11%, the same as in the MV grid. A second LV grid with only balanced inverters reached only a reduction of about 2% to 3%.

## CONCLUSIONS

SENSIBLE was a very challenging project where the significant effort of each single partner was decisive to reach the described success related to all project goals.

The Évora KPIs that related to losses minimization and quality-of-service, proved the huge potential of storage applications to grids. In terms of reliability, storage can enable islanding operation as a powerful tool to deal with extreme events affecting distribution grids, e.g. weather,. It was proven that storage is a key asset when dealing with high volatility both from generation and consumption, which affects voltage profiles, although the impact is different in LV and MV networks. Customers' flexibility was also proven to be of significant value when an emergency in the grid was detected, as it can be activated to negate the impact on the distribution grid.

The Nottingham demonstrator results showed, that large variations in ESS performance per household were dependant on a wide range of social and technical factors. Self-consumption and shifting energy between price periods was also shown to provide significant financial benefits, however, the later can increase the net CO2 emissions due to system losses.

With domestic level battery storage being a relatively new field, the Nottingham demonstrator showed that some commercial products are not fully matured yet and that significant improvements can be implemented.

Both Évora and Nottingham consumer engagement strategies proved to be effective as confirmed by the consumer awareness and engagement KPIs which are also linked to the socio-economic welfare benefits.

The Nuremberg demonstrator has proven the approach of negotiating a nominal building load profile with an energy supplier, DSO or other party, a day-ahead of the energy consumption. At the time of the energy consumption, the multi-energy-vector BEMS was shown to optimize the operation of the storage and generation infrastructure by using the remaining flexibility to deliver the forecasted load profile. In Nuremberg a cross-energy-vector building energy management system (BEMS) is demonstrated. The BEMS is based on a two-stage model-driven optimization approach: It first calculates a day-ahead energy system operation plan, and during operation, the BEMS continuously handles deviations from the plan. Three use-cases have been successfully demonstrated, showing increased self-consumption, optimal energy procurement, and enabling energy market participation of a building. The demonstrator uses the market platform and central forecasting services developed within SENSIBLE. The results show an increased self-consumption up to 12 % and a feed-in reduction of up to 51 %. The energy procurement costs are reduced by 5%.

Overall, the SENSIBLE demonstrators have shown that energy storage and energy management tools can provide additional energy services to end users, so that their flexibility can be evaluated on energy markets, which creates economic benefits for customers and opportunities for energy players to enter the energy markets. The experience gained from the demonstrators reinforced that standardization activities are required, particularly for the integration between storage devices and the ICT layer. Communication latencies, when dealing with huge amounts of data, were also a challenge which can be addressed by using a combination of centralized tools, distributed/local control and forecasting. Finally, it was demonstrated that the quality of forecasts, both load and generation, highly impacted the performance of the management systems in all three SENSIBLE domains.

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