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# E-LOBSTER

## Electric losses balancing through integrated storage and power electronics towards increased synergy between railways and electricity distribution networks

## Deliverable D5.1
## E-LOBSTER KPI Panel

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# Executive Summary

The main objective of the E-LOBSTER project is to develop and demonstrate up to TRL 6 in relevant environment (a real underground railway in Madrid connected to a local power distribution network with a high penetration of RES) an innovative, economically viable and easily replicable Electric Transport-Grid Inter-Connection System that properly managed will be able to establish mutual synergies between power distribution networks, electrified urban transport networks (metro, trams, light railways etc.) and charging stations for electric vehicles.

In particular, E-LOBSTER is going to demonstrate tools and technologies, software and hardware to assess the source of losses of both the networks (transport and electricity distribution networks ) prioritising techniques for their minimisation via a coordinated control of the power supply for electrified transport and recharge stations for electric cars and towards the maximisation of the local consumption of Renewable Energy Sources (RES) production thanks to the use of Electrical Energy Storage (EES) and advanced power electronics devices.

In its concept, E-LOBSTER project is proposing an innovative Railway to Grid Management system which, combined with advanced power electronics (smart Soft Open Point) and Battery Energy Storage systems, will be able to reduce electricity losses in both the power distribution network and the railway distribution network. The system will be able to make the best use of the available energy on both the grids by increasing their mutual synergies and maximizing the consumption of local Renewable Energy Sources (RES) production through electric energy storages.

The demonstration activities will be carried out in the framework of project work package 5 (WP5) where a step by step validation of the system will be carried out by validating first of all the smart Soft Open Point (sSOP), the Battery and the R+G Management System in the University of Newcastle Smart Grid laboratories and then by completing the demonstration in a real test case in Metro of Madrid premises. In the framework of this report, the E-LOBSTER KPI panel for assessing the project results after the installation of the sSOP, the Battery and the R+G Management System in the University of Newcastle Smart Grid laboratories and in the Metro of Madrid substation is provided.

The defined KPIs include the following:

- Reduction of the Energy Consumption from the Electricity Distribution Network
- Improvement of the Power Factors of the Supply Feeder at the Electricity Distribution Network
- Maximization of the Penetration Level of the Renewable Energy Sources

For each KPI, a systematic approach was presented in order to carry out the test case study required for each KPI as well as an assessment value was given for each KPI in order to evaluate the performance of the demonstrator under this KPI.

Finally, the investment of the ESS in the E0LOBSTER concept was economically studied by estimating the NPV analysis under different scenarios such as providing ancillary services to the distribution network or/and using the storage energy to charge EVs.

# 1 Introduction

The overall scope of the E-LOBSTER project is to develop and demonstrate an innovative, Electric Transport-Grid Inter-Connection System that properly managed will be able to establish mutual synergies between power distribution networks, electrified urban transport networks and charging stations for electric vehicles.

In particular, E-LOBSTER project is developing an innovative Railway to Grid (R+G) Management system which, combined with advanced power electronics (smart Soft Open Point) and Electric Energy Storage systems (ESS), will be able to reduce electricity losses in both the power distribution network and the railway distribution network and to make the best use of the available energy on both the grids by increasing their mutual synergies and maximizing the consumption of local Renewable Energy Sources (RES) production through electric energy storages.

The work package 5 (WP5) of the E-LOBSTER project will be directed to demonstrate a real-time platform to implement the E-LOBSTER system in the University of Newcastle Smart Grid Lab as well as in a substation environment at Metro de Madrid. Regarding the first objective, emulated rail energy models along with the Smart Soft Open Point (sSOP) hardware and the energy storage system (ESS) will be integrated into the smart grid laboratory. Consequently, the first design and development of the E-LOBSTER (both at hardware and software level) and the interconnection with the R+G management system will be carried out in order to be validated by University of Newcastle through its smart grid Laboratory.

The smart grid laboratory at University of Newcastle provides a connection to the physical electrical distribution network at 11kV. The physical network, energy storage and sSOP components will be combined with emulated behaviours (for both rail and electrical networks), using real-time network models and data in order to demonstrate the applicability of the solution in different cases. These case studies will demonstrate the system using an industrial connection in response to a variety of scenarios.

Several suitable key performance indicator (KPI) frameworks will be identified at the beginning of WP5 in order to evaluate the impact of the E-LOBSTER project and the achievement of project demonstration objectives. Environmental parameters such as avoided $CO_2$ emissions and primary energy savings will be also taken into account. After each demonstration step suitable recommendations coming from field testing will be highlighted in order to re-arrange both software and hardware E-LOBSTER components.

This deliverable, as a first deliverable in WP5, will outline the E-LOBSTER KPI panel and present number of KPIs to monitor the progress of the E-LOBSTER demonstration in order to evaluate its validity and applicability. The KPIs under consideration are included the following targets:

- Reduction of the Energy Consumption from the Electricity Distribution Network
- Improvement of the Power Factors of the Supply Feeder at the Electricity Distribution Network
- Maximization of the Penetration Level of the Renewable Energy Sources

## 1.1 Terms and Abbreviations

The following terms and abbreviations are used in this document.

| Term/abbreviation | Meaning |
|---|---|
| DSO | Distribution System Operator |
| ESS | Energy Storage System |
| KPI | Key Performance Indicator |
| MDM | Metro de Madrid |
| NPV | Net Present Value |
| RES | Renewable Energy Sources |
| sSOP | Smart Soft Open Point; refers to power electronics equipment that interconnects different energy systems in real-time only when the resulting energy flow is optimum. |
| UNEW | University of Newcastle |

## 1.2 E-LOBSTER Schematic at the Demonstrator in University of Newcastle

The single line diagram of the E-LOBSTER schematic of the demonstrator in EPT-Lab in University of Newcastle is illustrated in Fig.1.1.

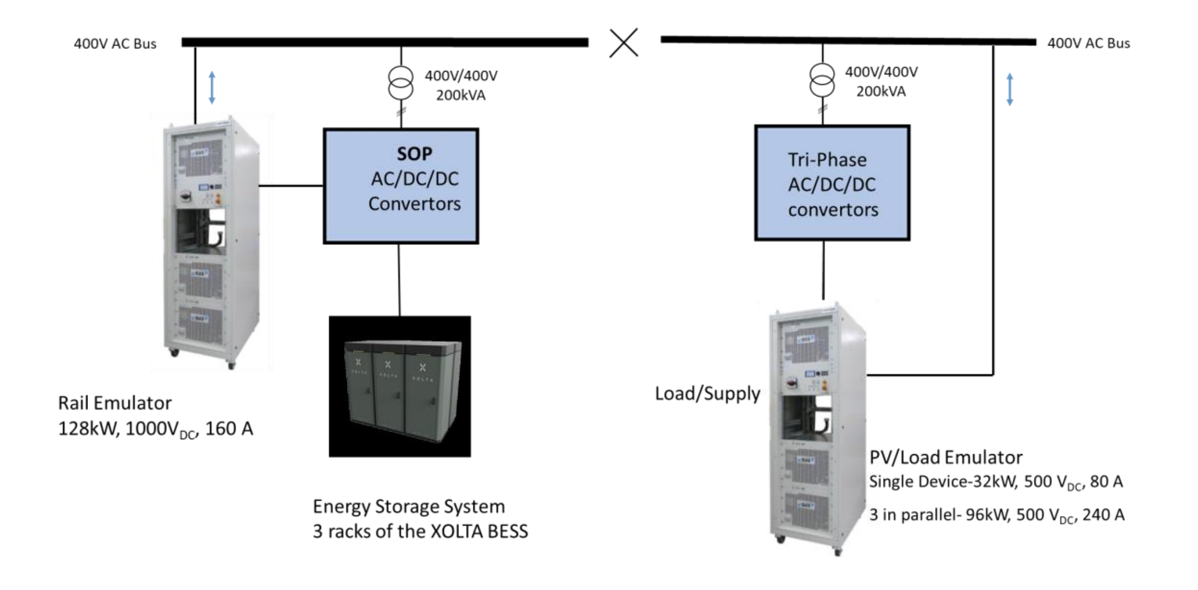



**Figure 1-1: Single line Diagram of the E-LOBSTER schematic of the Demonstrator at University of Newcastle**

The grid connection single line diagram of science central building is demonstrated in figure 1-2; the Energy Storage Test Bed (EPT- Lab) in Fig. 1-2 is connected to 400 V bus through two insulation transformers. It is clear that a number of loads are connected to 400 V bus which is also feeding EPT lab. The measurement available in the LAB are based on two insulation transformers in Fig.1-1, measuring Import/ Export of power flow to/ from SOP/ Tri-phase to 400 V bus.

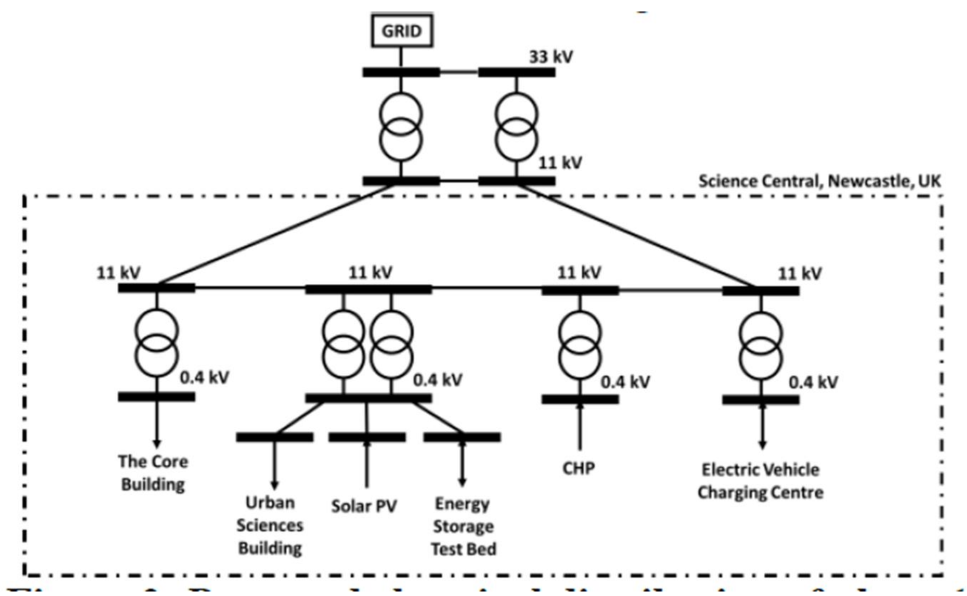



**Figure 1-2: Gird connection Single line Diagram of Science central building & EPT Lab in UNEW**

The REGATRON (GSS 32kW- Bidirectional High Power DC supply) will be used to emulate Rail behaviour and PV/Load. The example of system configuration is as follows:

Single device- 32kW, 500 $V_{DC}$, 80 A
System in parallel-(4 devices) 128 kW, 500 $V_{DC}$, 320 A
System in matrix- (4 devices) 128 kW, 1000 $V_{DC}$, 160 A
System in parallel- (3 devices) 96 kW, 500 $V_{DC}$, 240 A
System in series- (3 devices)96 kW, 1500 $V_{DC}$, 80 A

In the system configuration as Matrix, there 4 single devices which one of them acts as master and the other three will be slave. Based on the system configuration as shown in Fig.1-1, the rail behaviour will be modelled through the matrix configuration which will provide 128 kW, 1000 $V_{DC}$, 160A. This means the maximum voltage will be limited to 1000 V which is sufficient for emulation 600 V train behaviour. To emulate PV or load, single device or the parallel configuration of maximum 96 kW, 500 $V_{DC}$, 240 A can be applied. PV/ Load emulator will be connected to tri-phase system ( DC/ DC and DC/AC convertors) importing/ exporting energy to the 400 V grid in a way the power flow will be measured from one of transformers, however power will be go through 400V bus in Fig 1.2 not just circulated in the LAB. The 400 V bus will also feed REGATRON devices through another connection in the lab as shown in Fig 1.1. In this regards, E-LOBSTER management system needs to make sure the scenarios explained in KPI will be validated and tested properly.

The Tri-phase convertors are composed of DC/DC convertor of 90kW in maximum and DC/AC convertors of 180kVA in maximum connected through a DC link of 650 in normal operation as illustrated in Fig.1.3 for ESTB (Energy Storage Test Bed ) schematic. The configuration of E-LOBSTER in LAB will set up as shown in Fig1.1.

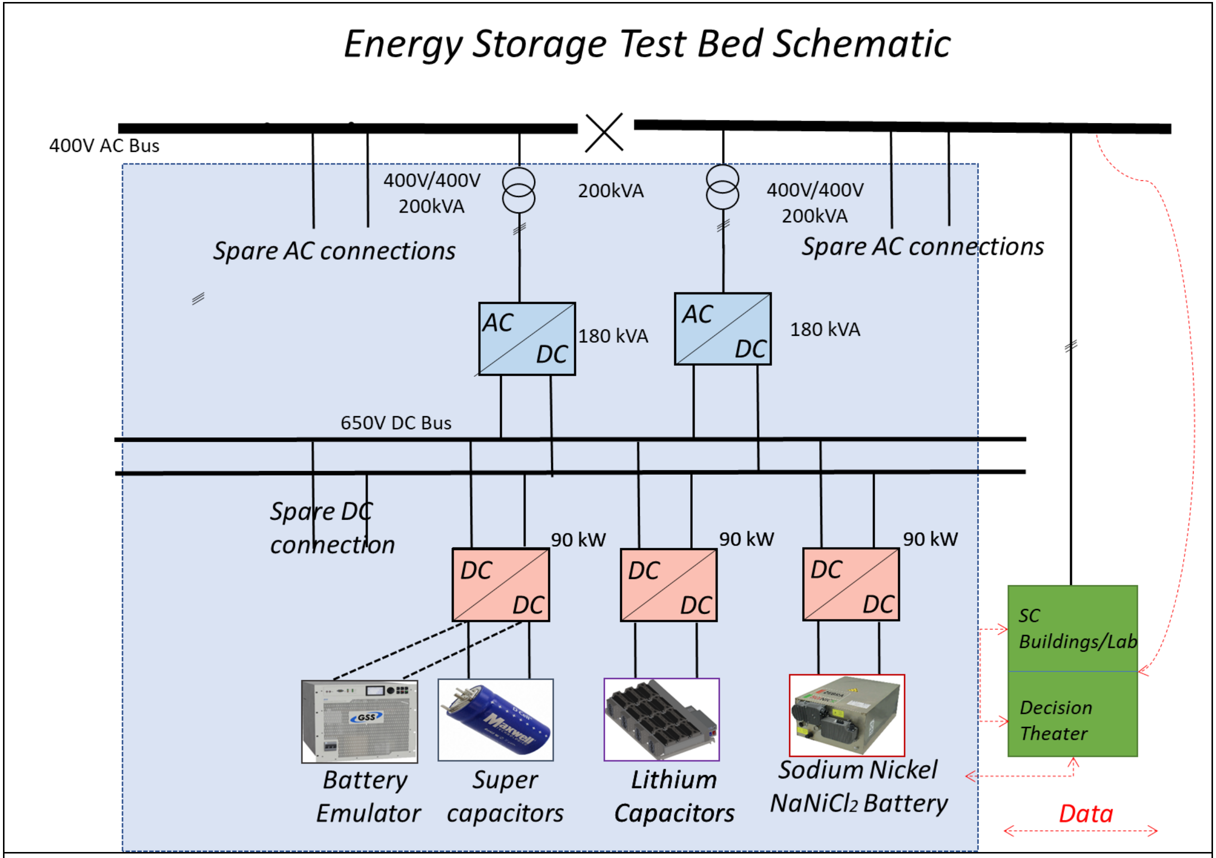



Fig 1.3- Energy Storage Test Bed (ESTB) Schematic

# 2 KPI (1): Reduction of the Energy Consumption from the Electricity Distribution Network

This KPI will analyse the amount of the electrical energy which could be provided from the railway network to the loads connected at the distribution network through the sSOP. This electrical energy is primarily generated during the braking of the trains in the railway network and was burnt in the on-board braking resistance in the trains. This amount of energy can be used to reduce the demands on the electricity distribution network while increasing the braking efficiency in the railway network.

In order to estimate this amount of energy in the E-LOBSTER demonstrator at University of Newcastle, the outcomes of the railway simulator will be adopted in which the railway simulator will simulate the Metro of Madrid line 9 and will provide the power and voltage profiles of the SACEDAL TPSS (Demo location at Metro of Madrid) including with installation of inverting substation which is equivalent to the sSOP operation in the E-LOBSTER demonstrator.

In the following subsections, the aforementioned procedures are identified in details.

## 2.1 Estimate the amount of energy supplied to the loads at Distribution network in Simulation Environment

Line 9 of Metro of Madrid is 39.4 km long with 29 stations (From Paco de Lucia to Arganda del Rey). There are two zones for line 9, which are Line 9a (from Paco de Lucia to Puerta de Arganda) and Line 9b (from Puerta de Arganda to Arganda del Rey). Different trains are operated in these two zones. This study will focus on the simulation analysis on line zone 9a.

The operating voltage of this line is 600 V DC. The overall voltage limit in the network are given in table 2-1. The total journey time for line 9a is around 40 min. The distance of the stations and the position of the traction power supply stations (TPSS) is shown in Table 2-2. There are 3 transformers for each substation (2 working and 1 in stand-by). The rated power of a transformer is 2400 kVA. There are 3 rectifiers connecting with each transformer. Each rectifier has a rated power of 2MW.

**Table 2-1 Network voltage limits**

| Parameters | Value/Equation |
|---|---|
| Lowest non-permanent voltage [V] | 400 |
| Lowest permanent voltage [V] | 480 |
| Nominal voltage [V] | 600 |
| Highest permanent voltage [V] | 720 |
| Highest non-permanent voltage [V] | 780 |

The DC electrification system has been characterised using the data supplied by MDM as well as from other traction power supplies with similar characteristics. The main parameters are reported in Table 2-3. The traction system of the train has been characterised using the data supplied by Metro of Madrid and are reported in Table 2-4 in which the overall train mass, train resistance and dwell time are estimated based on the similar trains from other sources. The train of line 9 is 9000 MRSSRM-Birension. The length of the train is 110 m with 6 carriages.

**Table 2-2 Location of the stations and the traction substations**

| | Station | Location [m] | TPSS | Voltage [V] |
|---|---|---|---|---|
| 1 | Paco de Lucía | 0 | | |
| 2 | Mirasierra | 1400 | yes | 600 |
| 3 | Herrera Oria | 2598 | | |
| 4 | Barrio del Pilar | 3559 | yes | 600 |
| 5 | Ventilla | 4592 | | |
| 6 | Plaza de Castilla | 5462 | | |
| 7 | Duque de Pastrana | 6080 | yes | 600 |
| 8 | Pío XII | 6832 | | |
| 9 | Colombia | 7541 | yes | 600 |
| 10 | Concha Espina | 8266 | | |
| 11 | Cruz del Rayo | 8979 | yes | 600 |
| 12 | Avenida de América | 9697 | | |
| 13 | Núñez de Balboa | 10427 | yes | 600 |
| 14 | Príncipe de Vergara | 11246 | yes | 600 |
| 15 | Ibiza | 11962 | | |
| 16 | Sainz de Baranda | 12918 | yes | 600 |
| 17 | Estrella | 13762 | yes | 600 |
| 18 | Vinateros | 14661 | | |
| 19 | Artilleros | 15522 | yes | 600 |
| 20 | Pavones | 16459 | | |
| 21 | Valdebernardo | 17875 | yes | 600 |
| 22 | Vicálvaro | 19257 | | |
| 23 | San Cipriano | 19768 | | |
| 24 | Puerta de Arganda | 20421 | yes | 600 |
| 25 | Rivas Urbanizaciones | 26213 | yes | 600 |
| 26 | Rivas Futura | 29737 | | |
| 27 | Rivas Vaciamadrid | 31311 | yes | 600 |
| 28 | La Poveda | 35693 | yes | 600 |
| 29 | Arganda del Rey | 39396 | yes | 600 |

**Table 2-3 Power network characteristics**

| Parameters | Data |
|---|---|
| Rectifier no load voltage [V] | 650 |
| Rectifier rated voltage [V] | 600 |
| Rectifier rating [MW] | 2 x 2MW |
| Rail track resistance [Ω/km] | 0.0145 |
| Rail resistance per 2 tracks [Ω/km] | 0.00725 |
| 3rd rail resistance [Ω/km] | 0.015 |

**Table 2-4 Train traction characteristics**

| Parameters | Value/Equation |
|---|---|
| Overall train mass [tonnes] | 300 |
| Train formation | 6 cars, M-R-S-S-R-M |
| Rotary allowance | 0.08 |
| Train resistance [N/tonne] | [2.418 0.028016*3.6 0.0006575*3.6^2] |
| Maximum acceleration rate [m/s] | 1.0 |
| Maximum braking rate [m/s] | 1.0 |
| Maximum traction power [kW] | 4500 |
| Maximum braking power [kW] | 4500 |
| Maximum operation speed [km/h] | 80 |
| Maximum tractive effort [kN] | 450 |
| Dwell time [seconds] | 30 |
| Auxiliary power [kW] | 180(maximum) |

The amount of electrical energy which could be supplied through the inverting substation in the simulation case study will be estimated in two different operating times; the on- and the off- operation times, in which during the on-peak time the headways varies from 4 to 5 minutes, while during the off-peak time the headway varies from 7 to 8 minutes.

For the on-peak operation time, a headway of 270 seconds is selected and the corresponding power and voltage profiles of the of the SACEDAL TPSS with inverting substation installed are illustrated in figure 2-1 (a) and (b) respectively. The inverting substation are activated within a voltage envelope form 670V to 720V and its power is represented as negative power in the shown figure.

Based on this simulated case study, the amount of electrical energy which is generated through the braking of the network trains and supplied through the inverting substation is calculated to be equal to 23.09 kWhr.

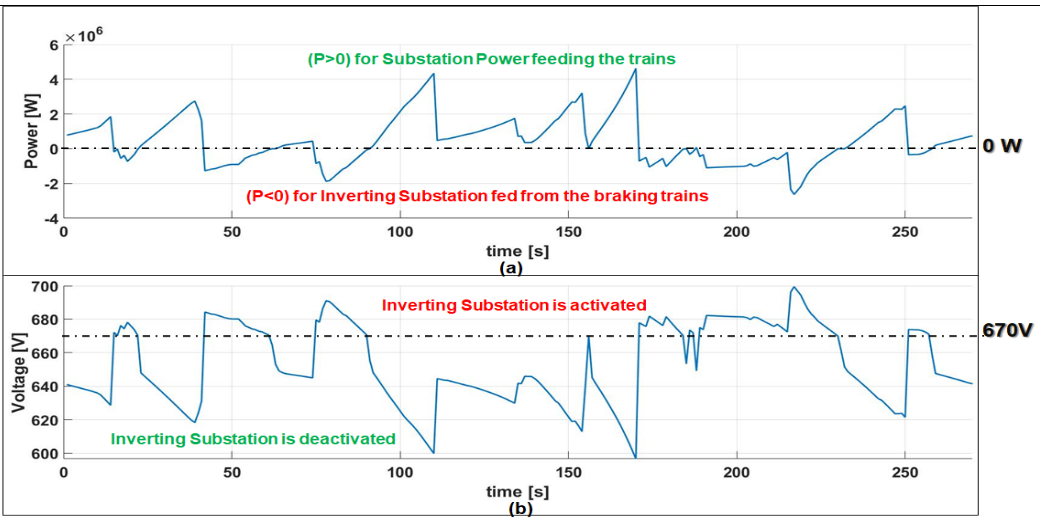



**Figure 2-1: Power (a) and voltage (b) profiles of the of the SACEDAL TPSS with inverting substation at headway 270 seconds (on-peak)**

Similarly, for the off-peak operation time, a headway of 440 seconds is chosen and its corresponding power and voltage profiles are shown in figure 2-2 (a) and (b) respectively for the SACEDAL TPSS with inverting substation installed. Consequently, the amount of electrical energy which is supplied through the inverting substation in this case study is calculated to be equal to 36.18 kWhr.

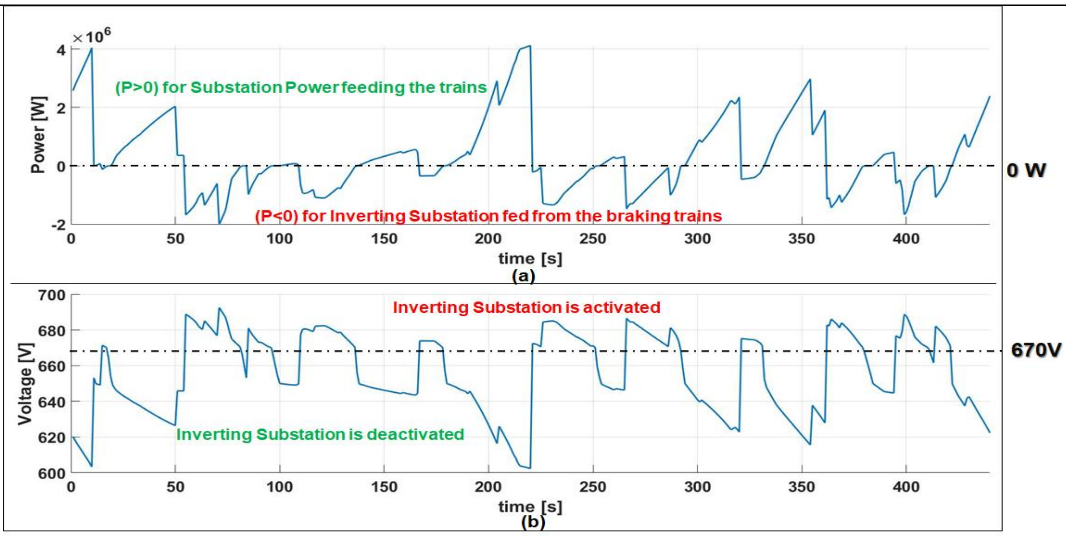



**Figure 2-2: Power (a) and voltage (b) profiles of the of the SACEDAL TPSS with inverting substation at headway 440 seconds (off-peak)**

Table 2-5 summarizes, for the both case studies, the amount of energies which could be reduced in the electricity distribution network by alternatively supplying them through the inverting substation installed at railway networks.

**Table 2-5 Energy Reduction in Simulation Case studies**

| Headway in seconds | Energy in kWH |
|---|---|
| 270 (on-peak) | 23.09 |
| 440 (off-peak) | 36.18 |

## 2.2 Quantify the amount of energy supplied through to the loads at the Distribution network in the Demonstrator

In order to implement this KPI at the E-LOBSTER demonstrator at UNEW and validate it against the outcome of the simulated case studies, a scale down approach will be applied to the output energies values given in Table 2-5. The scaling down process will be from the rating of the inverting substation (4 MW) assumed in the simulation environment down to the grid converter rating of the sSOP of the demonstrator (80 kW). As a result, equivalent energy values can be proposed for the E-LOBSTER demonstrator under this KPI. Table 2-6 summaries these energy values.

**Table 2-6 Energy Reduction in Simulation Case studies**

| Headway in seconds | Scaled down Energy in WH |
|---|---|
| 270 (on-peak) | $E_{inv\|\ on\text{-}peak} = 23.09 \times {}^{0.08}/_{4} = 462$ |
| 440 (off-peak) | $E_{inv\|\ off\text{-}peak} = 36.18 \times {}^{0.08}/_{4} = 724$ |

Accordingly, the following steps will be applied to implement this KPI in the demonstrator:

1. Provide the voltage profiles (fig. 2-1(b) and fig2-2(b)) of the SACEDAL TPSS to the railway emulator model the demonstrator.
2. Assess the activation of sSOP operation when the voltage lays between 670V and 720V
3. Measure the energy supplied through the sSOP ($E_{sSOP}$) at the two test conditions during its activation periods.
4. Finally validate in both test conditions that

$$\frac{E_{inv}}{2} \leq E_{sSOP} \leq E_{inv} \tag{1}$$

# 3 KPI (2): Improvement of the Power Factors of the Supply Feeder at the Electricity Distribution Network

In this section, the improvement in the power factor of the supply feeders at the distribution network will be investigated thanks to the sSOP operational control. The second KPI in this deliverable will asses the reactive power control of the sSOP grid inverter in order to support the distribution network if it is loaded with relatively high inductive loads. In the following subsections, a brief of the reactive power control of the grid inverter in sSOP will be introduced, then an inductive load will be proposed to be connected in the distribution network of the demonstrator at UNEW in order to validate the functionality of the sSOP under this KPI.

## 3.1 sSOP inverter reactive power control

An advanced sSOP control algorithm, allows to perform the additional functions of reactive power support, voltage support, power factor correction etc... Some of the benefits that can be realized by employing power management system consist of maintenance of network voltages within statutory limits, reducing power losses, improving load voltage profiles, improving power factor and avoiding overload condition at the transformers. These benefits result in the effective utilization of power distribution apparatus and minimise the need for traditional network reinforcement.

The reactive power demand is controlled directly by sSOP grid-side inverter. Reactive power demand is set by default to zero, which corresponds to unity Power Factor i.e. zero reactive power exchanged between sSOP and grid. Reactive power demand Q* can be set by power management system in way for example to improve the power factor of the feeder or transformer. Power Factor support only needs to operate when there is enough active power flowing in the cable. Feeders with low loads may have a low power factor but do not need compensating. The sSOP can also inject or absorb reactive power to compensate any inductive or capacitive loads. Theoretically, the converter can operate to cover the full power range in all four quadrants. The reactive power transfer is however limited by the inverter rated current, terminal AC voltage and amplitude of the DC-link voltage for the normal operating range.

The sSOP is rated for a maximum of 80kVA (116A RMS) with a power factor that can vary between (-0.7 to +0.7). The PQ operational area of the sSOP is, as mentioned above, dependent on the terminal voltage and inverter rated current. A simplified simulation model was run in PLECS to provide indicative PQ values with a nominal DC voltage of 775V. Three different values of sSOP terminal voltage were assumed: 216V, 230V and 253V RMS per phase. The PQ diagram of the sSOP is shown in figure 3-1.

## 3.2 Emulate a high inductive load in the distribution network at the Demonstrator

An emulated reactive load of 50kVAr can be utilized for this test case to be connected to the distribution network to evaluate this KPI. The reactive load will be modelled through two Regatron devices which using Tri-phase system a reactive load will be emulated. According to the specifications of the grid inverter of sSOP given in subsection 3.1, the maximum reactive power which it could be provided equal to

$$Q_{max} = \sqrt{S_{max}^2 - P_{min}^2} = \sqrt{80^2 - (80 \times 0.7)^2} = 57.13\ kVAR \qquad (2)$$

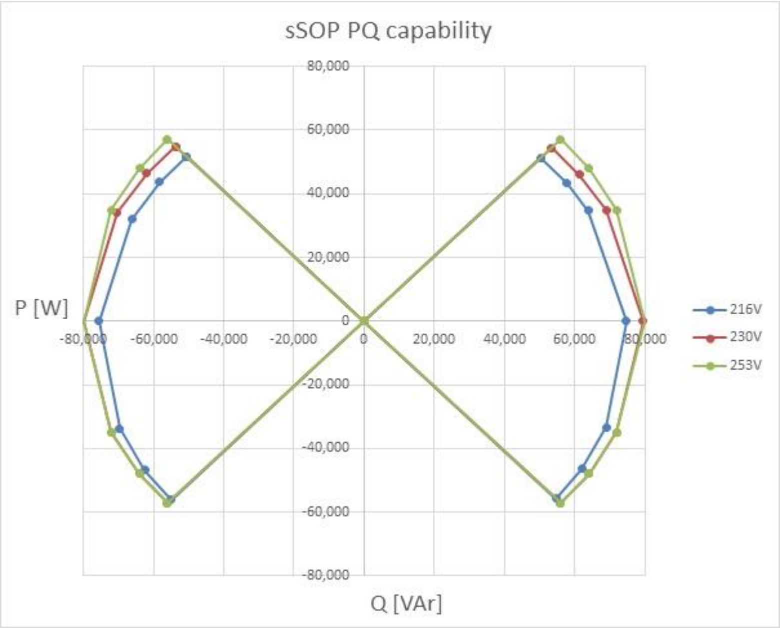



Figure 3-1 sSOP PQ capability at grid terminal voltage of 216V in blue, 230V in red, and 253 in green

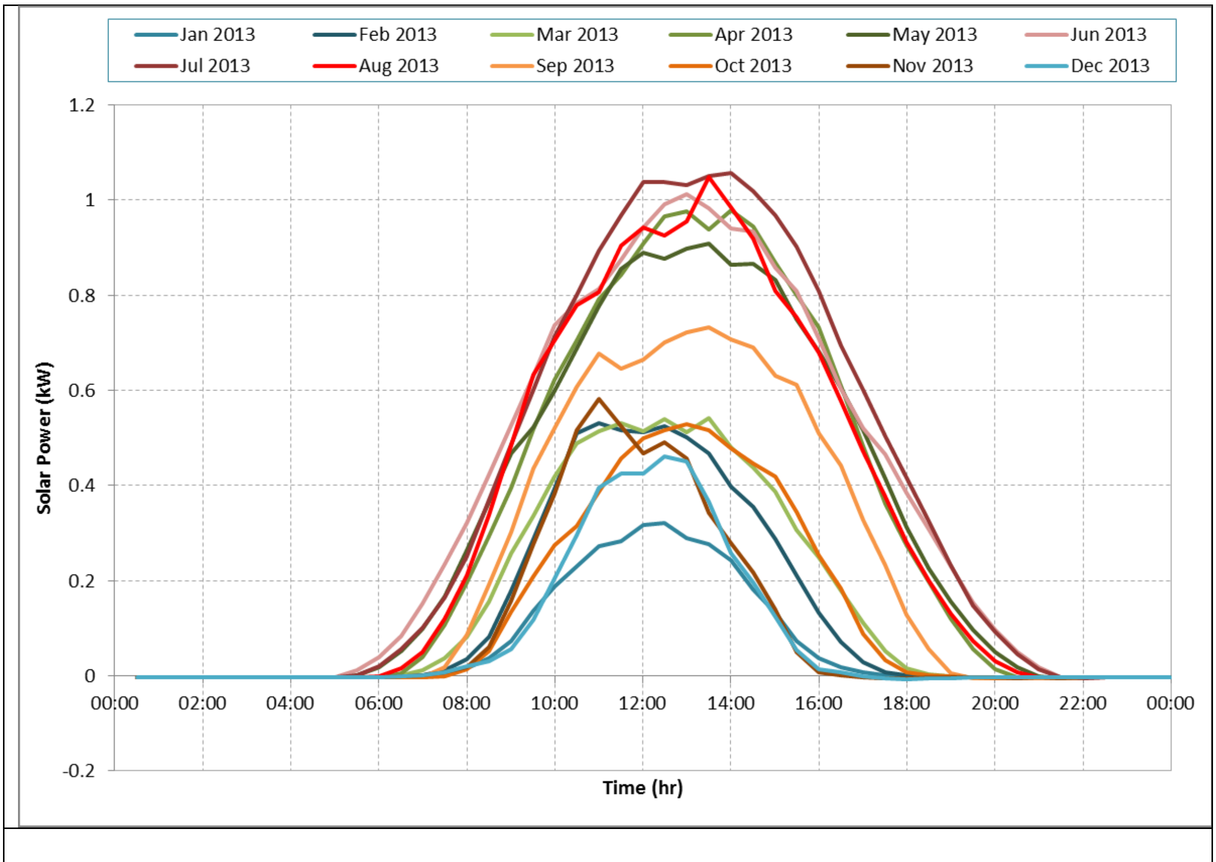
Consequently, the power factor at the 400 V supply feeder (i.e. at the secondary of the 11KV/400V distribution transformer) will be measured twice during this case study as follows:

1. $P.F_1$ without the connection of sSOP in the demonstrator
2. $P.F_2$ with the connection of the sSOP in the demonstrator
3. Finally validate that

$$P.F_1 < P.F_2 \leq 1 \tag{3}$$

# 4 KPI (3): Maximization of the Penetration Level of the Renewable Energy Sources

To investigate the impact of renewable energy sources in terms of solar energy, a set of PV data will be implemented and emulated through REGATRON. PV generation has a strong relationship between season and maximum generation happens in summertime. To illustrate the PV generation in different seasons, a data set is plotted from CLNR (Customer Led Network Revolution) in UK in Figure 4-1, Monthly solar PV generation profiles have been produced within the dataset to show variability of generation across 2013 on a month-by month for solar PV customers in CLNR project. For example, as demonstrated in Fig.4.1, the peak is changing from 1.06kW in July to 0.3 kW in January for a domestic household. Also, PV will generate power from sunrise to sunset which in summer is from 07:00 am to 19:00 in average and in winter from 9:00 am to 15:00 pm.




In E-LOBSTER, a similar data set will be produced to investigate the impact of renewable resources and the data set will be emulated through Regatron using a single device of 32kW or 48 kW if two of them is configured as parallel. The emulator (DC) will be connected to Tri-phase (DC/DC, DC/AC) and then the energy will be transferred to 400V bus of network through another isolation/ insulation transformer. The energy flow from emulator will be measured through transformers in Fig.1.1. The DC/DC Tri-phase converter in maximum will be able to transfer 90 kW and DC/AC converter is able to transfer 180 kVA in maximum which are quite sufficient for the E-LOBSTER project. To generate more than 50 kW generation from PV data, it will be needed to look for 3 of REGATRON devices to set up as parallel producing 96 kW in maximum generation. This will be further investigated if it is needed to scale up.

# 5 Economic analysis in the investment of the electric storage systems of the E-LOBSTER

The economic KPI is seeking to put a value on the energy captured from regenerative braking of a train and stored in the battery system. This energy could be bid on the market (e.g. ancillary services market) and bring profits to the potential investor.
The economic KPI will be determined based on the net present value (NPV) analysis of the investment in the E-LOBSTER solution. In the NPV analysis, all single cash flows are discounted to year 0 and they are cumulated once they are made comparable. NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project. Positive values of NPV indicate the profitability of the investment.

$$NPV = \sum_{n=1}^{j} P = F_n \frac{1}{(1+i)^n} \tag{4}$$

where:
$P$ is the present worth
$F$ is the future worth
$i$ is the interest rate
$n$ year in which cash flow occurs
$j$ number of years for NPV analysis (e.g. lifetime of the E-LOBSTER solution)

The NPV from the investment in the E-LOBSTER solution will be calculated for scenarios where:
1. profits are generated by providing ancillary services in the grid (frequency regulation, a balancing market, etc.);
2. profits are generated by energy trading agreement with a third-party behind the meter (e.g. EV charging stations, renewables support);
3. profits are generated by combinations of different scenarios;

The profitability of investment in the E-LOBSTERsolution is dependent on many technical, economic and regulatory variables. So, the NPV calculated for the demonstrator site (Metro of Madrid) will be different than NPV calculated for other locations and other local regulatory conditions. Thus, the other goal of this KPI would be also to perform sensitivity analysis to determine which factors are having the highest impact on the profitability of the E-lobster solution. The considered factors for the sensitivity analysis of the NPV KPI are:
- number of trains and number of stations (start, stop);
- investment cost of the E-lobster solution - storage size (power/energy) and sSOP size (power);
- energy selling price;
- E-LOBSTER solution efficiency;

# 6 Conclusions

In this deliverable, the single line diagram of the E-LOBSTER demonstrator in University of Newcastle is firstly illustrated with the specifications of the emulator units that will be used for representing the railway network as well as the load and renewables connected to the distribution network.
Afterwards, three main KPIs are studied and analysed to asses and evaluate the effectiveness of the E-LOBSTER concept. These KPIs include the following:

- Reduction of the Energy Consumption from the Electricity Distribution Network
- Improvement of the Power Factors of the Supply Feeder at the Electricity Distribution Network
- Maximization of the Penetration Level of the Renewable Energy Sources

For each KPI, a systematic approach is presented in order to carry out the test case study required for each KPI as well as an assessment value is given for each KPI in order to evaluate the performance of the demonstrator under this KPI.
Finally, the investment of the ESS in the E0LOBSTER concept is economically studied by estimating the NPV analysis under different scenarios such as providing ancillary services to the distribution network or/and using the storage energy to charge EVs.