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E-LOBSTER

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

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Analysis of the interaction between Railway energy and distribution networks in terms of flow of electricity: challenges and limitations

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Abbreviations

Abbreviation	Description
ESS	Energy Storage System
DAS	Draving Advisory System
RMS	Root Mean Square
NGESO	National Grid Electricity System Operator

1 Introduction

The main objective of the E-LOBSTER project is to develop and demonstrate 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. By properly managing the integrated system, it will be possible 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 will demonstrate tools and technologies, software and hardware to monitor in real time the source of losses of both the networks (Transport and distribution networks) prioritising techniques for their minimisation via a coordinated control of the power supply for electrified transport and recharge stations for electric cars, towards the maximisation of the local consumption of Renewable Energy Sources (RES) production thanks to the use of Electrical Energy Storages (EES) and advanced power electronics devices.

This report analyses and identifies all possible shared degrees-of-freedom between Railway Energy Network and Distribution Electricity Network. According to the energy losses identification and localization, the global electric framework, the constraints and the degrees-of-freedom of both the railway electric grid and the electric distribution network are investigated in order to analyse how to make them interact minimizing electrical losses and in a mutually beneficial way. The analysis of degrees-of-freedom of railway electric grid considers train scheduling, over-tension related to the start/stop of trains etc., while the analysis of degrees-of-freedom of electric distribution network considers quality of the power, frequency level, traditional daily supply scheduling etc.

By evaluating and identifying the degrees of freedom that can be utilised to reduce losses of each network independently, the correlation between the two networks and the essential methods to reduce the power losses of the integrated system can be understood. This report lays out the ground for the further development of the integrated R+G (Railway-to-grid) Management System.

2 Identification of the degrees of freedom for the railway network losses reduction

2.1 Influence of train timetable on voltage profile and power losses

2.1.1 General introduction on losses

Since 2011, Network Rail has undertaken various studies investigating the primary drivers of electrical losses on both their AC & DC Networks. A 2011 study estimated the average value of electrical losses in AC Networks to be 5%[1] and DC losses to be 21%.

The report states that due to various factors and variables that contribute to energy losses, values for approximate energy losses cannot be derived from pure calculation and must also be based on elements engineering judgement and probability derivation.

The Network Rail report "Estimate of DC losses: Electricity Supply Tariff Area Analysis[2]" postulates that electrical losses can be considered as a combination of fixed and variable losses. Fixed losses are constant and occur all the time the network is energised, while variable losses occur when current is flowing predominantly as a result of trains drawing traction energy. Variable losses often take the form of resistive I2R losses

The following table is a summary of results of a Network Rail & Southern report on Booz Class 377 testing, which concluded that 27% was the best estimate for traction losses based on understanding at that time of loads and system configurations.

Table 2-1 Summary of Booz Study Results – Southern area

Source	Uplift	Total	HV	Transformer Rectifier	Con rail	Return rail	Leakage allowance
Booz class 377	26.6%	21%	1%	3%	10%	5%	2%

The following table outlines the results of three discrete modelling simulations of the southern DC network in order to conclude values for average I2R losses

[1] Summary – Stage 1 Measurement of Electrification System Losses ac network.

[2] *Estimate of DC losses: Electricity Supply Tariff Area Analysis*– CP5 proposal, Network Rail

Table 2-2 Summary Table – ESTA U Modelling Simulations

Summary Table - ETST U Modelling Simulations							
ESTA U - Single Train Modelling Variable I^2 R Losses			ESTA U - Sussex Multi-Train Modelling Variable I^2R Losses (06:30 - 09:30)			ESTA U - Mult-Train Modelling Variable I^2R Losses (04:00 - 11:00)	
Configuration	% Range	% Median	Timetable	Low Service Density % loss	High Service Density % Loss	Area	% Loss
4 car	4 to 11	7.5	2007	13.3	10.6	Inner London	9.3
8 car	6 to 16	11	2013	12.8	12.2	Outer Sussex	10.7
12 car	9 to 21	15	2018	12.7	11.32	Outer Kent	7.9
Average % modelling loss		**11.17**	**Average % modelling loss**	**12.93**	**11.37**	**Average % modelling loss**	**9.3**

Network Rail have also done work with the University of Birmingham in modelling DC variable losses. Simulations were run for 3, 6, 9, & 12 car trains

The graph below shows the results of these 4 simulations. From this, an average value of the 6 car simulation as well as additional engineering knowledge can be used to derive an appropriate value of an average of 6.2% I2R losses.

Figure 2-1 Results of Mersey Rail DC Loss Simulations

A 2011 study on AC Electrification concluded that 5% was an appropriate estimate for traction losses within the network. The following table outlines the estimated AC losses from this study[3].

[3] Estimate of AC losses: Electricity Supply Tariff Area Analysis, Network Rail

Table 2-3 Summary Table – ESTA U Modelling Simulations

Estimation of Overall Losses	
Factor	**Estimated Value**
Resistive Losses	3%
Leakage	1.2%
Commercial	Up to 1.5%
Power Quality Equipment	0.53%
Adjustment for BT system	Up to 1.7%
Total	**4% to 6%**

2.1.2 Technology analysis

The design of schedules is a method whereby energy consumption can be reduced without additional cost; this makes this measure one of the best methods to reduce energy consumption.

It is necessary to clarify that this measure does not work alone; actually the use of the regenerative brake is a crucial condition for any energy reduction.

There are three aspects that have to be taken into account to reduce energy consumption. The first one is related to the margins of regularity and their compatibility with Eco-driving; while the other two are related to the coincidence between departures, or between departures and arrivals at the same station.[4]

(I) Frame times match with Eco-driving:

Doing an efficient and economical driving consists in taking full advantages of the degrees of freedom offered by the timetables (journey time) in order to reduce energy consumption.[5]

Moreover, the train schedules need “regularly margins” to be more robust and reliable. As the margin of regularity is often larger than the one needed for Eco-driving margin, it is possible to leave a small amount of time for performing an Eco-driving strategy where there is no scheduling requirement, and distributing the rest of the frame time between the points that require punctuality. Another possibility is to reduce time at stops and adding the reduced time to the Eco-driving time frame.

(II) Avoiding simultaneous departures:

The several tracks of the same station are normally fed from the same substation, even in some cases several stations are fed by the same substation, as it can be seen in Figure 2-2.

[4] García, A. (2016). Energía y emisiones en el transporte por ferrocarril. Fundación de los Ferrocarriles Españoles. Madrid (Spain).

[5] UIC. Energy efficiency technology for railways. Railway energy.

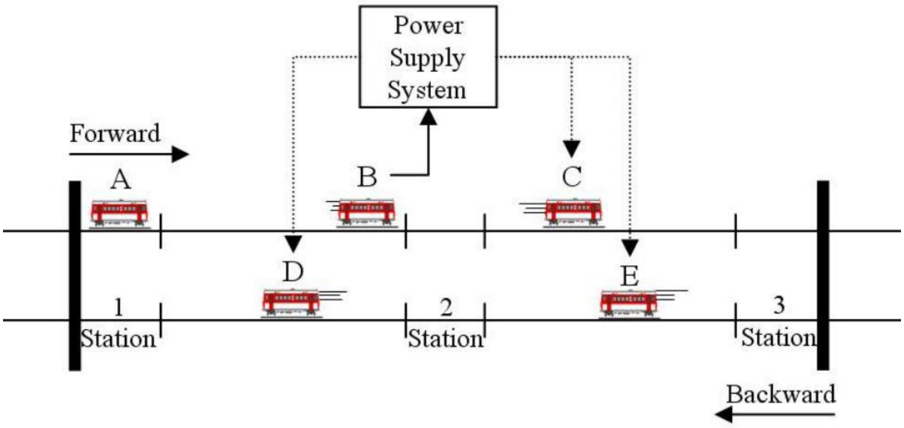

Figure 2-2 Group of stations.[6]

Therefore, if a simultaneous departure of multiple trains occurs, an increase in the power peak required is produced, which implies an increase of the ohmic losses, and consequently the energy required is bigger. Moreover, an installation of higher power is required and therefore an increase of the investment is needed, as is shown in Figure 2-3.

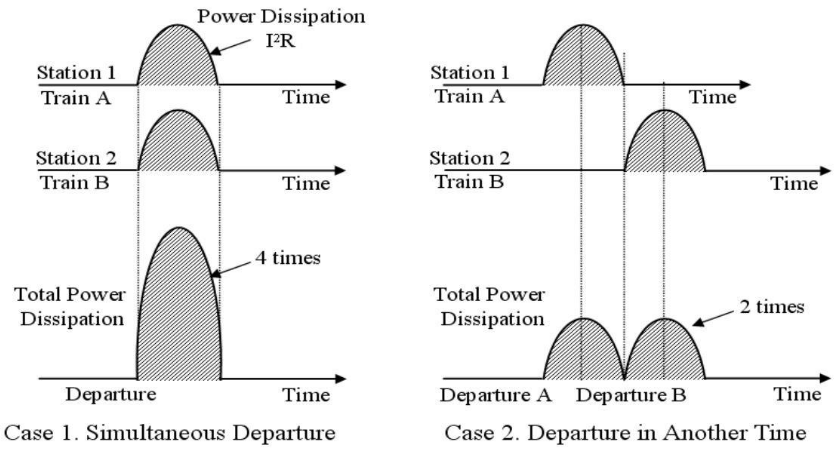

Figure 2-3: Power dissipation in traction phase.

(III) Match arrivals and departures at the same station.

In a line with frequent stops and trains with regenerative brake, simultaneous departure and arrival in the same station at the same time, energy saving can be facilitated, since the energy regenerated by the train arriving (brake) may be exploited by trains leaving the stations (accelerate)[7], as is shown in Figure 2-4.

[6] Kim, K. M. et al. (2010). A Model and Approaches for Synchronized Energy Saving in Timetabling.

[7] Fernández-Cardador, A. et al. (2008). Sincronización de arranques y paradas en metropolitanos para el uso eficiente del frenado regenerativo. II Jornadas Estrategias de Ahorro y Eficiencia Energética en el Transporte Ferroviario. 5-6 June 2008. Sitges (Spain).

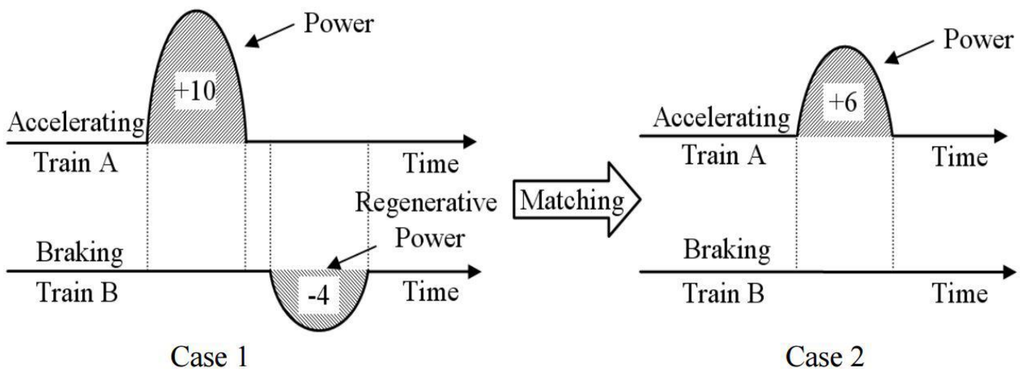

Figure 2-4: An example for synchronized driving

<u>(IV) Models of energy losses in electrified urban rail networks</u>

A primary cause of energy losses in power supply systems are losses in auxiliary systems. These losses are greater than resistance losses, traction losses and braking losses. Metro systems commonly regenerate energy from kinetic energy back to electrical energy either by itself, stored in on board energy systems or transmitted back to the overhead line network. Research into the reduction of traction energy losses focuses on two fronts, cutting down on initial losses and increasing the yield of usable regenerative energy.

The diagram below shows a model that approximates power losses in traction systems, with considerations for regenerative energy systems.

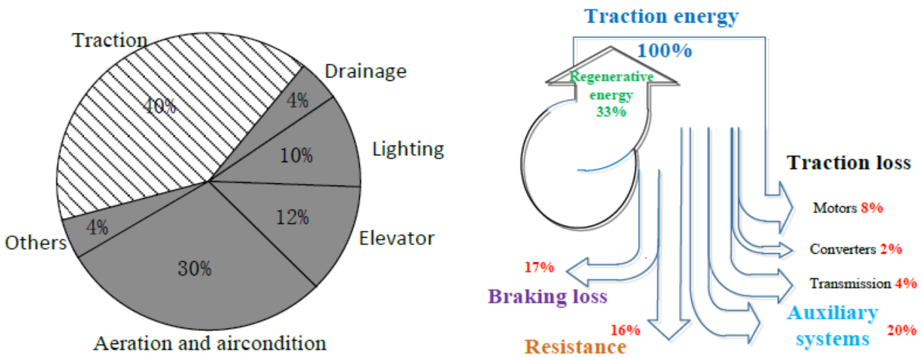

Figure 2-5 Energy consumption in metro systems

The following diagram is an outline of different power losses in a typical traction power simulation[8]. This model states that majority of power losses in traction systems, 50%, can be attributed to braking energy losses. Of these losses, two thirds of this is recoverable; with the rest, lost in friction brakes, motors, and the transmission system, cannot be recovered back into the system.

[8] Z. Tian, G. Zhang, N. Zhao, S. Hillmansen, P. Tricoli and C. Roberts, "Energy Evaluation for DC Railway Systems with Inverting Substations," 2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), Nottingham, 2018, pp. 1-6.

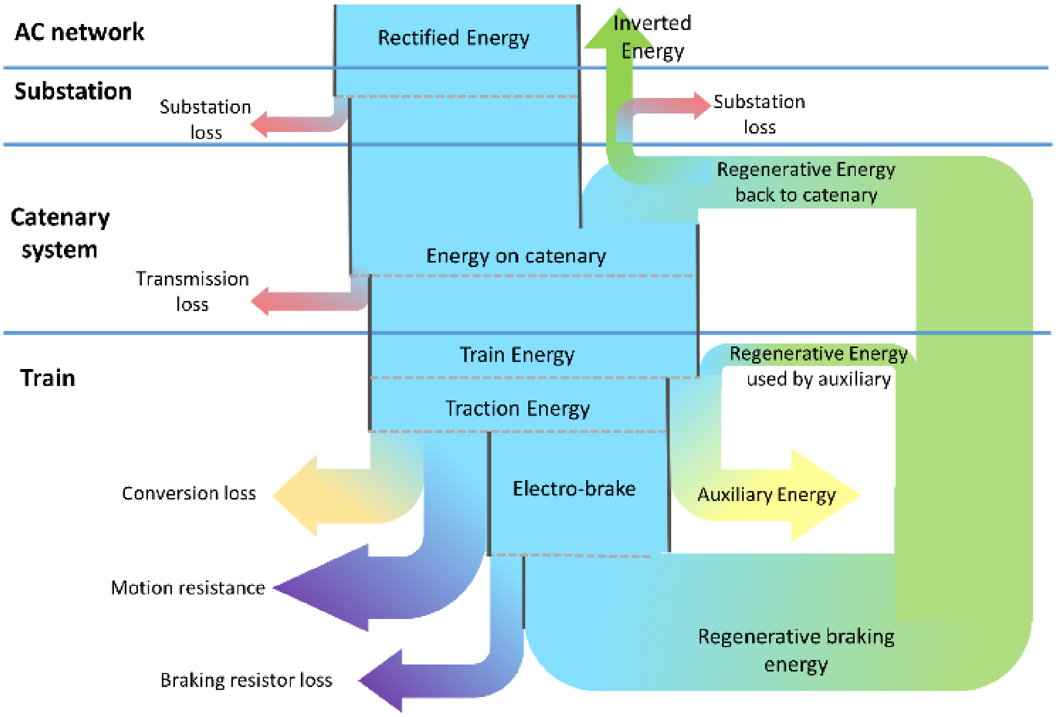

Figure 2-6 Typical traction energy flow in urban rail systems

(V) Strategies and Methodologies of Reducing Traction Losses in Metro Systems

Timetables for subway systems and similar urban rail networks are designed around passenger demand; which determines train capacity, fleet size and trip duration. There have been various investigations into the integration between train control and timetable design, with various methodologies and models for optimising train timetabling. However, many of these models assume traction and braking forces to be constant, and so are limited in scope and can only be used for single train operation.

The diagram below outlines one method of optimising train operation through timetable scheduling, consisting of a three layer model[9].

[9] Su, S., Tang, T., Li, X. and Gao, Z., 2014. Optimization of multitrain operations in a subway system. IEEE Transactions on Intelligent Transportation Systems, 15(2), pp.673-684.

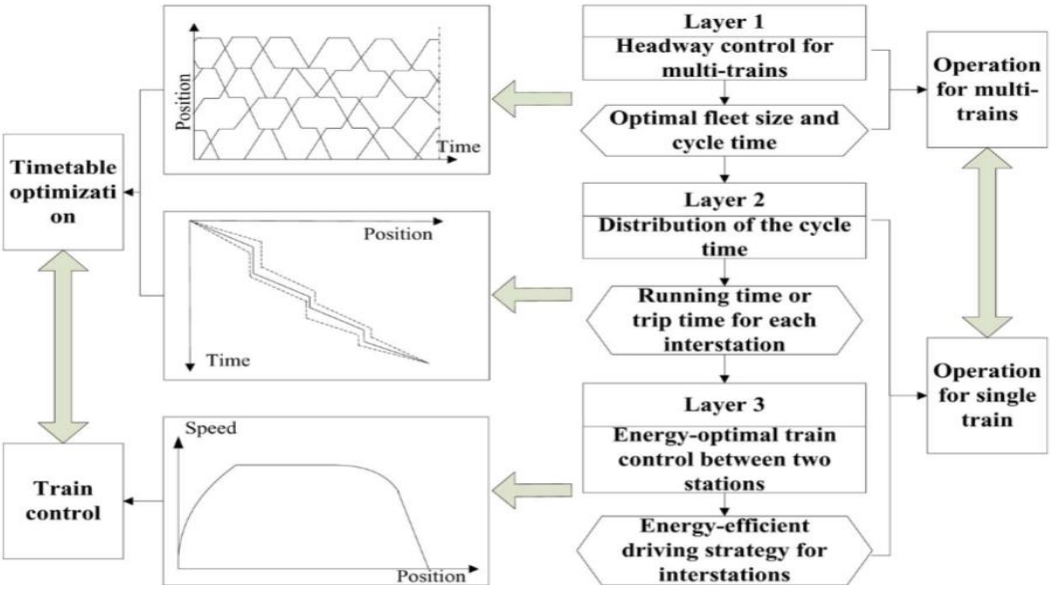

Figure 2-7 Three layers for energy-efficient train operation

Newer train operation models are designed for more complex applications. In 2013 researchers from Beijing Jiaotong University published a report detailing a model created multi-train operation analysis[10]. It is claimed that models such as these will be an improvement since they first integrate the fleet size and cycle time decision, distribution of cycle time, and driving strategy optimization. A case study based on operation data of the Beijing Yizhuang Subway Line shows that the proposed approach can reduce the energy consumption by 24.0% on average for the whole day.

Table 2-4 Evaluated Energy-Efficient Strategies. Beijing Yizhuang Line

Factors	Strategies	Energy-Saving%
Trip time	Timetable optimization	3.5
Train mass	10% reduction	7
Gradient	Optimized slopes distance	2
Maximum traction force	Increase by 10%	3
Maximum braking force	Increase by 5%	1.5
Regenerative braking	Installation ESSs	15
Regenerative braking	Timetable optimization	11
Running resistance	15% reduction	3

2.1.3 Objectives and benefits

Time compatibility can help reduce the energy consumption and energy costs, with a similar travel time and almost zero investment.

[10] Su, S., Tang, T. and Wang, Y., 2016. Evaluation of strategies to reducing traction energy consumption of metro systems using an optimal train control simulation model. Energies, 9(2), p.105.

Table 2-5 shows a simulation between Madrid and Zaragoza in which, with minimal changes on the timetable in arrival and departure times at the inter-stations, it is possible to perform an Eco-driving strategy[11], which implies an energy reduction of approximately 33.33%.[12]

	Commercial timetable with flat-out driving				Optimised timetable with energy efficient driving			
	timetable Ri hh:mm:ss	Flat-out time Rmi hh:mm:ss	Slack time hh:mm:ss	Energy consump. flat-out kWh	Opt. timetable Ri hh:mm:ss	Designed slack time hh:mm:ss	Opt. energy consump.n kWh	Energy savings %
Madrid-Guada.	00:23:00	00:18:48	00:04:12	1,690.826	00:21:04	00:02:15	1,245.029	26,37%
Guada.-Cala.	00:39:00	00:35:15	00:02:45	2,730.136	00:41:04	00:04:49	1,835.773	32,76%
Cala.-Zrg	00:26:00	00:22:26	00:03:34	1,445.056	00:25:52	00:03:26	841.643	41,76%
Total	1:28:00	1:17:30	0:10:30	5,866.02	1:28:00	0:10:30	3,922.455	33.63%

Table 2-5: Results of journey times and energy consumptions for commercial and optimised timetable.

Table 2-6 shows the energy savings in a simulation performed in line 3 in Madrid subway. It is important to notice that the total savings are approximately of 3,5%, this reduction is lower than expected, as the schedule is made with a frame time of one minute with respect to the original schedule. This new timetable allows coordinating arrivals and departures; while one train is arriving other is departing. This measure also implies that the power peak at the substation is considerably lower, with respect to the original schedule, due to the affordable use of the regenerated energy.[13]

	Energy consumption (kWh)		
Substation	**Inicial h.**	**Designed h.**	**Differences**
SUB 1	767	694	10.33%
SUB 2	2,308	2,261	2.01%
SUB 3	4,000	3,917	2.60%
SUB 4	3,806	3,472	9.43%
SUB 5	4,361	4,417	-1.38%
SUB 6	2,703	2,578	4.87%
Total	**17,944**	**17,333**	**3.52%**

Table 2-6: Average of the total energy consumption at substation.[14]

Figure 2-8 shows the block diagram for optimising train energy.

[11] IMPROVING THE ENERGY EFFICIENCY OF THE RAILWAY SYSTEM. The Best of “Railenergy".
[12] Sicre, C. et al. (2010). A method to optimise train energy consumption combining manual energy efficient driving and scheduling. Madrid (Spain).
[13] Plan de eficiencia energética del metro de Madrid (2013). Madrid (Spain).
[14] Peña, M. et al. (2010). Diseño de horarios ferroviarios para maximizar el aprovechamiento de energía procedente de sistemas de frenado regenerativo (Spain).

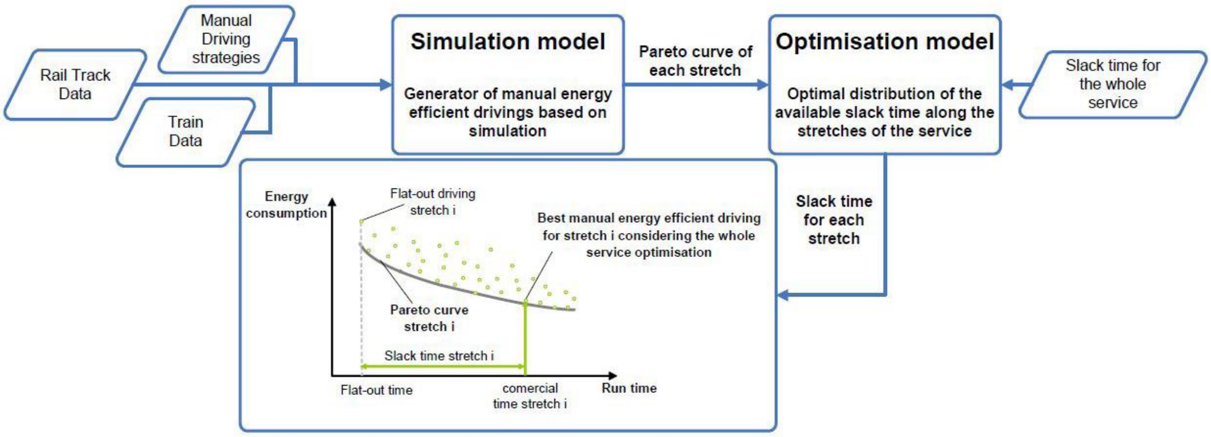

Figure 2-8: Block diagram for optimising train energy consumption.

2.1.4 Applications

In the table below it is possible to see diverse real applications or demonstrations from literature for this technology in different countries around the world. It is shown the author a small explanation of the application and the benefits of the implementation.

Author	Explanation	Benefits
K. M. Kim (2010)	This paper that proposes a mathematical approach that can increase energy saving in timetables. The energy-efficient timetabling method maintains the planned traveling time between stations, but coordinates the train departure times at the starting station from current timetable to minimize the power peak and simultaneously to maximize the re-usage of regenerative energy.	The model is verified using real data of Seoul Metro line 4. It can reduce the power peak up to 40%, and in addition, it can improve the re-usage of re-generative energy approximately 5%.
Siemens and the Technical University Berlin	Metromiser is a driving advisory system for suburban and metro systems developed by Siemens and the Technical University of Berlin. The Metromiser consists of two components: an on-board unit (OBU) and the timetable optimiser (TTO): The timetable optimiser is an off-board based software program checking the energy efficiency of timetables. Using basic data (acceleration, rolling behaviour of the train, topology, passenger flows, etc.) it draws up a new energy-optimised timetable fitting in with the existing running schedule of the railway network.	The study claims an average of 15% of every saving achieved with the use of Metromiser.
Peña, M. et al. (2010)	It has developed the model of economic gears for the efficient operation of the lines in rush hours, maximizing energy savings by implementing coasting orders remotor velocity and reduced brake parables, managing travel times and downtimes in station allowing to reduce the energy consumption.	This synchronized schedule was implemented in test mode for a week and the energy savings at substations were 3% less over time unsynchronized.

2.2 Impact of driving styles of trains on the average and instantaneous line voltage

2.2.1 Energy-efficient driving styles

Using energy-efficient driving styles can reduce the traction energy consumption. Figure 2-9 compares the traction power and energy with various speed profiles. All three operations take the same running time but have different energy consumption costs. From the speed trajectory curves, the first driving cruises at the highest speed (80 km/h) and coasts until it reaches the lowest speed (48 km/h), while the third driving style cruises at the lowest speed (66 km/h) and coasts until it reaches the highest speed (56 km/h). However, the second driving style costs the lowest energy, followed by the first driving style. The tractive energy profile shows the energy consumption during running. As shown in Table 2-7, the first driving style with a higher cruising speed leads to higher motion energy loss (5.95 kWh). This is because the high-speed running increases the motion resistance. With the same journey time, a high cruising speed leads to late braking. Thus, the kinetic energy may be reduced, which is 1.91 kWh for the first driving style. As for the third driving style, the motion loss is lower, but the kinetic energy is higher resulting in the highest total tractive energy consumption. Therefore, a balance between cruising speed and braking speed needs to be considered, and the best combination should be found. With the lower traction energy consumption, the power demand from trains decreases. Therefore, the average line voltage increases. However, the maximum traction power demand from each train does not change, which does not improve the lowest instantaneous line voltage.

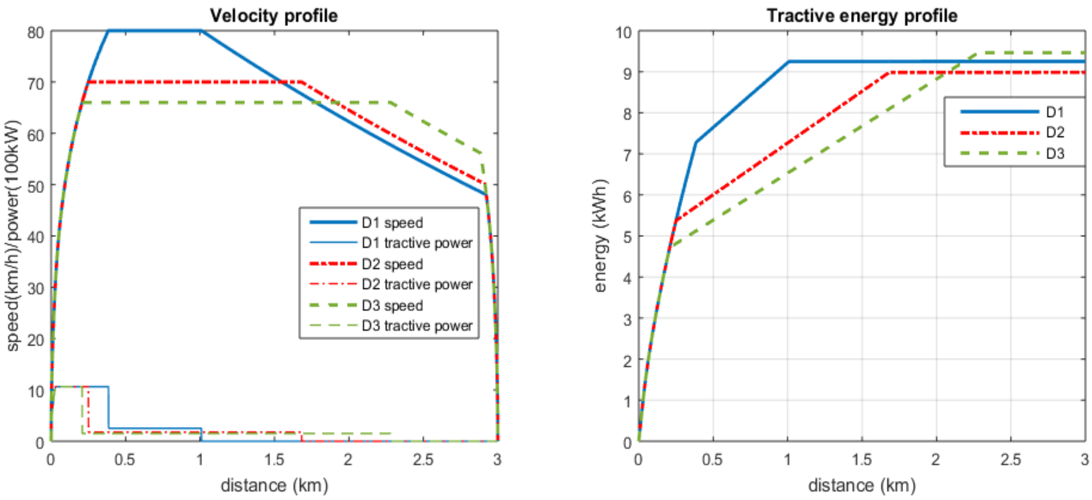

Figure 2-9 Speed and energy diagram of different driving patterns[15]

Table 2-7 Results of different driving patterns

Driving pattern	D1	D2	D3
Distance (km)	3	3	3
Journey time (s)	180	180	180

[15] Z. Tian, N. Zhao, S. Hillmansen, C. Roberts, T. Dowens, and C. Kerr, "SmartDrive: Traction Energy Optimization and Applications in Rail Systems," IEEE Transactions on Intelligent Transportation Systems, 2019 (Early Access, DOI: 10.1109/TITS.2019.2897279).

Cruising speed (km/h)	80	70	66
Braking speed (km/h)	48	50	56
Traction energy (kWh)	9.25	8.98	9.46
Traction loss (kWh)	1.39	1.35	1.42
Motion loss (kWh)	5.95	5.55	5.45
Kinetic energy (kWh)	1.91	2.08	2.59

2.2.2 Impact of acceleration/braking rate

Simulation results applying different acceleration/braking rate are shown in Figure 2-10 to Figure 2-12. Various acceleration rates only change the time of reaching maximum power, but not change the maximum power. For example, in Figure 2-10 with acceleration rate of 0.8 m/s^2, the maximum power is reached when the distance is 0.11 km, while in Figure 2-12 with acceleration rate of 1.2 m/s^2, the maximum power is reached when the distance is 0.035 km. The maximum power in these figures are the same as 2439 kW. Due to the maximum of power demand does not change, the lowest instantaneous line voltage is not improved.

Therefore, changing train driving styles or acceleration/braking rate can affect the average line voltage a little but cannot change the instantaneous line voltage level significantly. The line voltage is determined by load location and power. The maximum train traction power and the multiple trains locations are the main factors of line voltage.

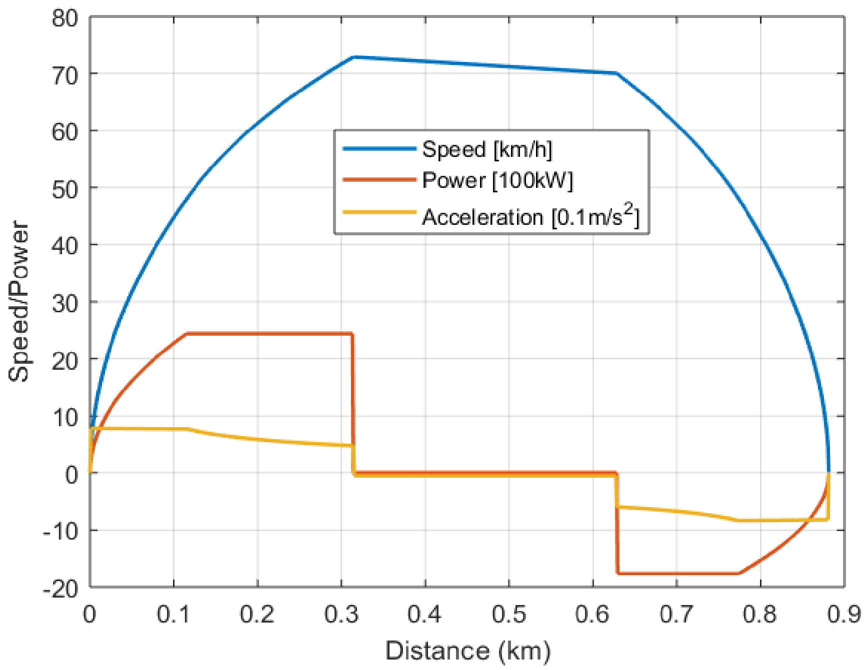

Figure 2-10 Speed and power profile when maximum acceleration rate is 0.8 m/s^2

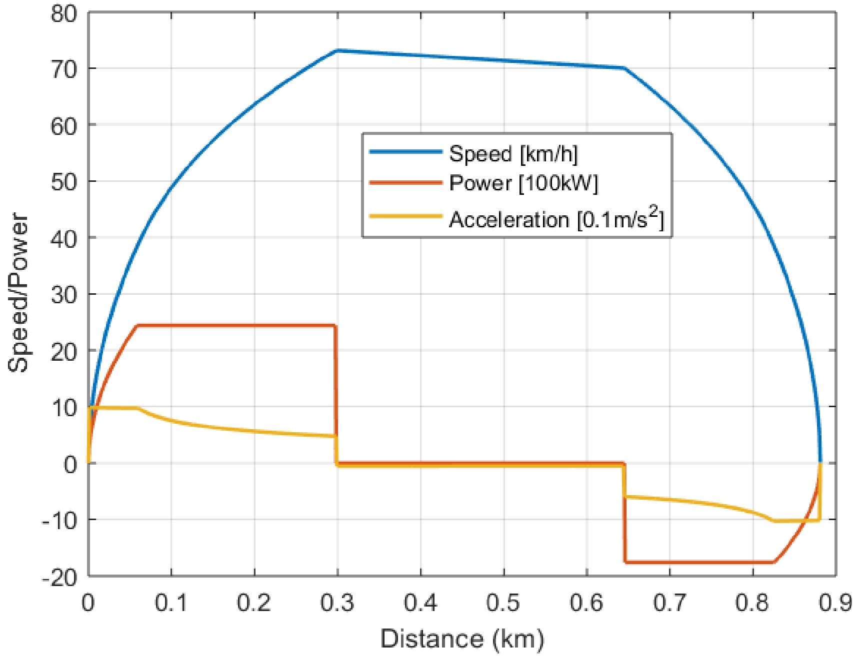

Figure 2-11 Speed and power profile when maximum acceleration rate is 1 m/s²

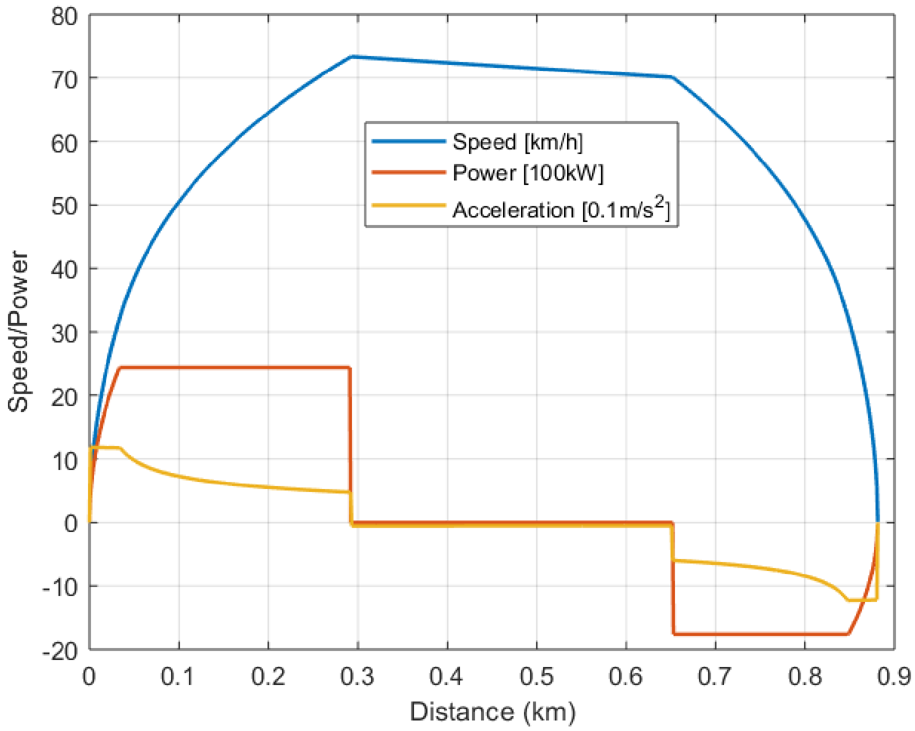

Figure 2-12 Speed and power profile when maximum acceleration rate is 1.2 m/s²

2.3 Influence of train hotel loads on power losses

2.3.1 On board HVAC

2.3.1.1 Technology analysis

Railway vehicles are equipped with several auxiliary systems that provide comfort to passengers and help deliver a better transport service. These auxiliary systems (also known as 'hotel loads') include lighting, automatic doors, loudspeakers, etc. Although traction usually consumes the biggest share of the total energy supplied to a train, the share of energy devoted to power auxiliary systems is significant, and may range from 10-15% to almost 50% of the total energy.

Heating, Ventilation and Air Conditioning systems (HVAC) are by far the biggest energy consumer of all auxiliary systems, as they usually represent up to 80% of all hotel loads.[16] Therefore, the efficiency of HVAC systems have a great impact on the overall energy consumption of a train.

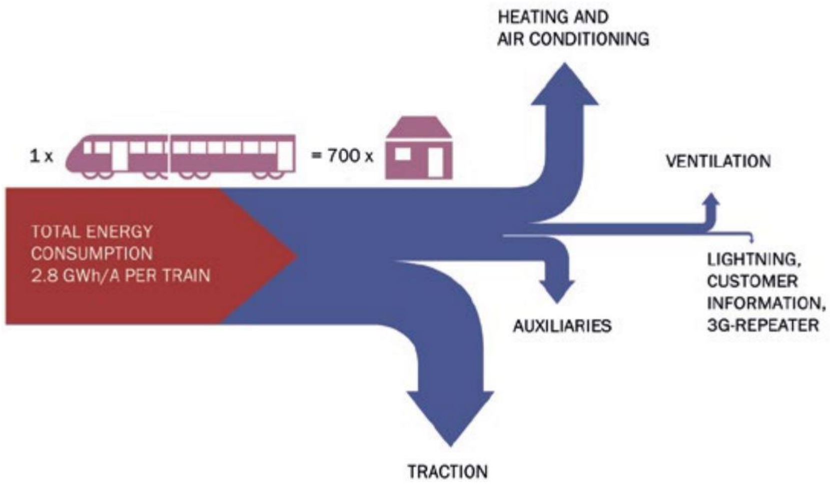

Figure 2-13: Example of energy consumption distribution on a train.[17]

There are several different HVAC configurations within the railway sector as there is little standardization of such systems. However, most of them are based on the same basic principle of heat transfer and consist of a condenser and an evaporator.

The compressor (4) pumps the refrigerant into the condenser (1), where it heats up and energy is released to the air. The refrigerant then passes through the expansion valve (2) into the evaporator (3) where it evaporates into a cold gas, thus extracting heat from the ambient air.[18] Multiple different configurations and variants are built upon this basic scheme.

[16] Martínez, P. et al. (2015). Measuring and modelling energy consumption in metro trains by means of neural networks. 13th Railway Engineering Conference. Edinburgh, Scotland, UK, June 30 – July 1, 2015.
[17] UIC (2015). Railway Handbook 2015. Energy Consumption and CO2 emissions. Available at: http://uic.org/energy-and-co2-emissions (accessed 27/07/2016).
[18] Schaffler. Air conditioner power systems for rail. Available at: http://www.schaffler.com (accessed 27/07/2016).

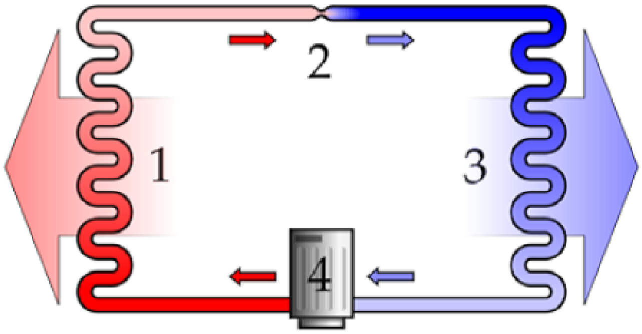

Figure 2-14: Basic HVAC configuration. 1) Condenser. 2) Expansion valve. 3) Evaporator. 4) Compressor.

2.3.1.2 Objectives and benefits

HVAC systems are heavy energy consumers, and have the biggest impact on the overall train energy consumption of all non-traction loads. There is an ongoing research being carried out by manufactures to increase the efficiency of their products. The following measures are proposed to reduce the energy consumed by HVAC systems:

- New refrigerants.

Most HVAC systems are filled with a refrigerant liquid that passes through the heat cycle and helps transferring heat from hot to cold sections. Traditional refrigerants such as R-22 (Hydrochlorofluorocarbon) were used extensively in the past, but due to their adverse effect on the ozone they are being actively substituted with less damaging gases such as R-410A (Hydrofluorocarbon). These gases allow higher air conditioning performance, hence reducing power consumption. Newer, natural refrigerants such as R744 (liquid carbon dioxide) or HFO-1234yf (2,3,3,3-Tetrafluoropropene) are currently being tested and preliminary prototypes shown even more reduction of GHG emissions and energy consumption.

- Smart HVAC management.

CO_2 monitoring is becoming standard practice and may help reducing energy costs by cutting off peak heating and cooling loads. By installing CO_2 sensors, the on board HVAC system can control the air quality and estimate the number of passengers in real time. With this information, the system is capable of adjusting fresh air intake from the outside and regulates temperature more accurately according to passenger needs, hence reducing energy consumption. Some estimations and models calculate energy savings between 15% and 30%.

Figure 2-15: HVAC unit.[19]

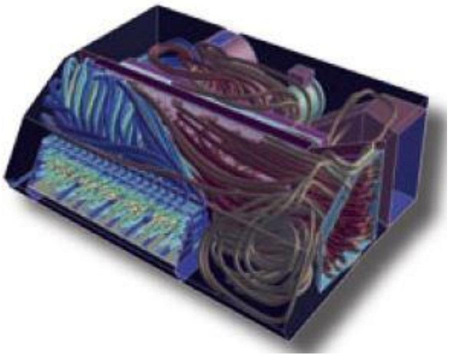

Figure 2-16: Computational Fluid Dynamic (CFD) studies of HVAC unit.

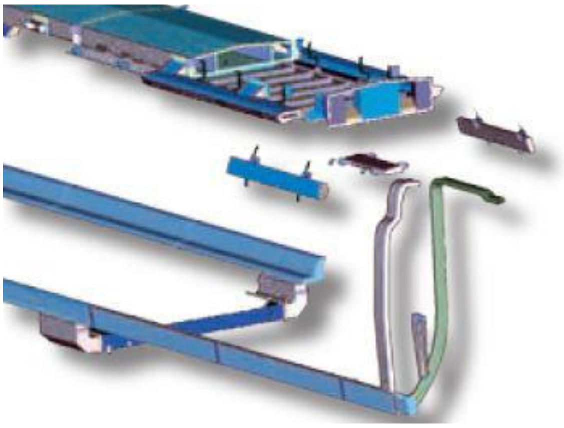

Figure 2-17: 3D Ducting Works.

2.3.1.3 Applications

In the table below it is possible to see diverse real applications or demonstrations from literature for this technology in different countries around the world. It is sown the author a small explanation of the application and the benefits of the implementation.

[19] http://www.merak-sa.com/es/index.jsp

Author	Explanation	Benefits
University of Basel Swiss Federal Office of Energy Swiss Federal Office of Transport	About 20% to 40% of electricity consumed by Swiss trains is used for HVAC. Aiming at the improvement of efficiency, heat losses were monitored and modelled and several improvements were proposed, such as better insulation and the installation of heat recovery systems. Reduction of outdoor air flow rate by means of CO_2 control was also proposed.	According to simulations, the implementation of all the measures proposed showed a saving potential of 40%. For the whole fleet of EWII vehicles operated by Swiss Rhaetian Railway, this yields an annual saving potential of 840 MWh.[20]
City Transport Operator (BVG) Liebherr-Transportation Systems	Liebherr will equip one of Berlin trams with an experimental occupancy-dependent fresh air control based on CO2 sensors that estimate the number of passengers and regulate the intake of fresh air.	This new system is expected to reduce HVAC energy consumption by 13%.

2.3.2 Train lighting system

2.3.2.1 Technology analysis

Although lighting is not the biggest energy consumer on board trains, averaging only 4% of the energy demand of comfort functions, it is possible to improve features such as functionality, energy efficiency, design, maintenance and environmental impact by means of adopting new technologies in lighting systems.
With energy efficiency becoming increasingly important in recent years, demand is growing for the adoption of LED lighting as a replacement for fluorescent interior lighting in passenger trains.

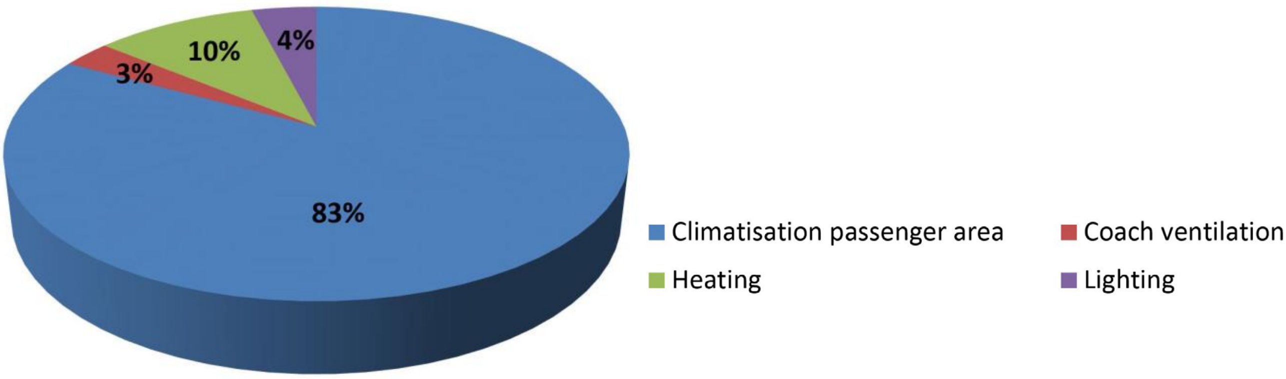

Figure 2-18 - Energy demand of comfort functions in trains.[21]

[20] Vetterli, N et al. (2015). Energy efficiency of railway vehicles. CISBAT, Lausanne, Switzerland, September 9-11, 2015.
[21] EVENT - Evaluation of Energy Efficiency Technologies for Rolling Stock and Train Operation of Railways Final Report submitted to the Subcommission Energy Efficiency. UIC

Taking as a reference the Japanese Industrial Standard for lighting levels in rolling stock, for passenger train interiors, the standard stipulates 200 lx or more at a height of 850 mm above the floor. The wavelength of LED light (roughly 450 to 500 nm) is shorter than that of fluorescent light (roughly 550 nm), and this gives it a characteristic bluish tint. Because the light is whiter than fluorescent lighting with emission intensity about 1.3 times stronger, text and similar on illuminated objects have a crispier appearance than when fluorescent lighting is used.
On the other hand, because it is produced in a discharge tube, fluorescent lighting has a spread of 360°. In contrast, the angle of light spread for typical LED lighting is approximately 120°, only about one-third than that of fluorescent lighting. This means that, compared to fluorescent lighting, there is little illumination intensity to be gained by using a reflector with an LED light.

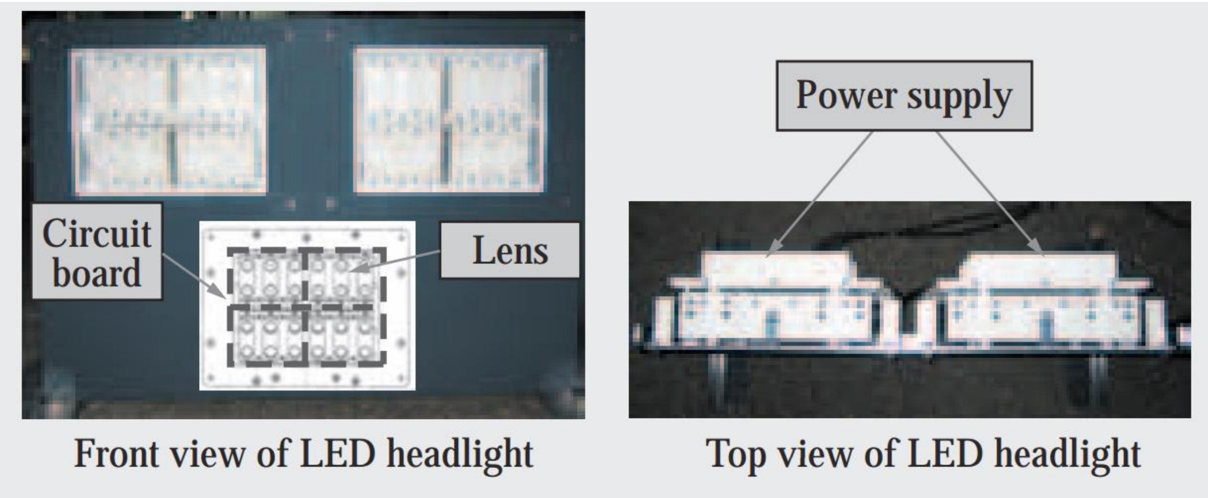

Figure 2-19: LED Headlight Design where the highlight is split into four blocks: upper blocks for high beam and lower blocks for low beam.

Finally, it is worth noting that, currently, halogen lamps or high-intensity discharge (HID) lamps are used for train headlights to improve forward visibility. However, these need to be replaced annually, and in the worst cases, once every three months. Because of their importance for ensuring safety, headlights should be replaced using LED equipment in order to provide excellent visibility and longer life cycle.

2.3.2.2 Objectives and benefits

The purpose of installing LED technology on board trains is to get some advantages with respect to conventional lighting systems that are listed below:

- Lower power consumption

LED lighting is more energy efficient than fluorescent lighting, cutting energy costs and carbon dioxide (CO_2) emissions almost by half.

- Elimination of flickering

LED lighting is ideal for use in trains because it is powered by direct-current (DC) electric power and does not produce the flickering that occurs with fluorescent lighting. This should reduce eye strain.

- No emission of ultraviolet rays

As the spectrum of light produced by LEDs depends on the semiconductor and phosphor material, unlike most other light sources such as fluorescent and incandescent lighting, it does not include any of the ultraviolet or infrared rays that do not provide any illumination. Similarly, it is also less prone to attracting insects because it produces very little ultraviolet light in the part of the spectrum visible to insects. This means that LED lamps are less prone to insect related dirt.

• Reduction in life cycle costs

As the life cycle of a LED element is approximately 40,000 hours, it significantly reduces the work associated with the frequent replacement, lighting on/off control, stock control, and waste disposal tasks that are an issue for halogen, fluorescent, and other forms of conventional lighting.

The lifetime of a LED lighting system is defined as the point at which the brightness falls to 70% of its initial level. As the principle of operation of LED lighting systems means that they are not subject to the phenomenon of burn out that occurs on halogen and fluorescent light bulbs, they do not need to be replaced before reaching their design lifespan. Similarly, it is not necessary to keep spares on hand in case of light bulbs burning out.

Finally, as the intensity of LED light is roughly proportional to the electric current, it is possible to establish circuit designs and devices that keep the current low without loss of light intensity, getting as a result an approximate 40% to 60% reduction in power consumption compared to fluorescent lighting.

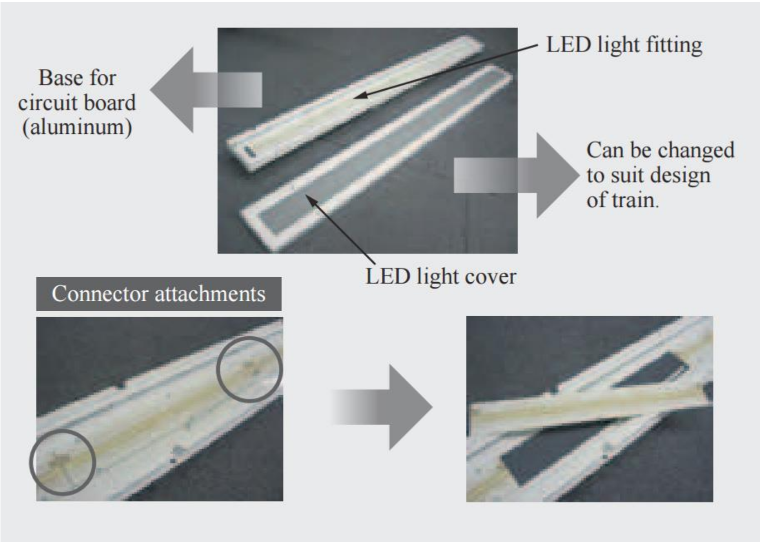

Figure 2-20: LED Light Design and LED Circuit Board.[22]

2.3.2.3 Applications

In the following table, it is possible to see diverse real applications or demonstrations from literature for this technology in different countries around the world. It is sown the author a small explanation of the application and the benefits of the implementation.

[22] Ishii, I. et al. (2012). LED Lighting System for Rolling Stock. Hitachi Review.

Author	Explanation	Benefits
Hitachi (Japan)	Hitachi intends to continue developing and designing rolling stock systems for easier maintenance and superior energy efficiency in order to provide operators with efficiency improvements while also improving passenger comfort by taking into account the entire rolling stock system. In this way, the company has develop a LED lighting system improved with circuit designs and devices that keep the current low without loss of light intensity.	The new developed LED features circuit and board configurations that are resistant to the effects of heat and designed for long life, reaching a life span of 100,000 hours (16 years) instead of 40,000 hours (typical for conventional LED).
Osaka Municipal Subway Midosuji Line (Tokyo)	About 30,000 railway vehicles are scheduled to go into operation in the fall of 2016 with Kawasaki's newly developed LED lighting and air purification system.[23]	The new LED lighting system achieves outstanding energy efficiency and passenger comfort. It will be the first to adopt a cherry blossom-light on a railway vehicle. The pale-pink light has the effect of reducing stress caused by being exposed to artificial light, as well as providing a sense of healing and being easy on the eyes.

2.4 Strategies to mitigate power losses for traction and non-traction use

2.4.1 Strategies to mitigate power losses for traction use

The energy used for traction accounts for around 60% to 70% of total railway energy consumption. Many different measures and technologies have a large impact on reducing energy consumption and therefore CO_2 emissions in the railway sector, some of them are grouped into these four main areas:

1. Measures related to the design of the infrastructure, installations and rolling stock:

- The design of an efficient infrastructure may reduce the use of the brake, which means a reduction of losses. For example, the existence of an upward gradient at the entrance of a station may imply savings of **5% in tractive energy** consumption and **23% in braking energy** García Alvarez, A (2009).
- Design of trains considering new train architectures that allow reducing drag resistance. An aerodynamic drag reduction of 25% may lead to a **15% of less traction energy usage**.
- Introduction of new materials that allow decreasing, for example, the total weight of the rolling stock, which will help to reduce the energy consumption. Composite materials meet stringent requirements even at aggressive operating conditions and, at the same time, may reduce a **5% of energy consumption** and CO2 emissions.
- Use of the renewable sources for non-traction loads, such as workshops, stations, may have a significant impact on the CO2 emissions. For instance, there are a 2.2 mile long tunnel that cross Antwerp in Belgium which is fitted with 16,000 panels between that are installed over on the roof. This installation could generate 3.3 MWh of electricity annually

Kawasaki (2015). Kawasaki Develops New LED Lighting and Air Purification Systems for Rolling Stock. Kawasaki news and events. December 2015..

and help to save about **2,400 tons of CO2 per year.** They provide enough electricity to power 4,000 trains a year and for lighting, signals and other infrastructure.

- On GB mainline DC third rail network, various measures have been looked at historically to mitigate against DC traction losses. In the early 1990s, then British Rail worked with Brecknell Willis to develop third Al conductor rail. This was subsequently used on Hooton – Chester / Ellesmere Port electrification (on MerseyRail), reducing the need for additional two new substations. Furthermore, similar conductor rail was used in Fareham Branch to negate the need to upgrade the power system. In both these cases, due to low impedance of the Al conductor rail compared to Steel helped reduce the I2R losses and also ensure the system voltage was adequately high to run train services. In the recent years, there has been a push to retrofit trains' vehicles (where financially justified) with regenerative braking and with the new rolling stock effectively being regenerative braking capable (Refer to T58024). Anecdotal evidence shows that the DC network by its design and dense train network is receptive to the regenerative braking energy and therefore no additional infrastructure such as reversible substations or any storage devices have been installed on the DC network.

<u>2. Measures related to power traction. Among them, the following can be highlighted</u>:

- Electrifying those railway lines that are not electrified can bring to electric traction gross tons that currently are transported by diesel traction. According to Network Rail (2009, there is a decrease between **19% and 33%** in CO2 emissions.
- Reduction of losses in the traction chain due to the deployment of new technologies. The use of more advanced technologies (i.e. AC asynchronous traction motor with IGBT inverters) may lead an increase of the efficiency and a reduction of **15% of the energy consumption.**
- Inclusion of reversible substations in the power supply system, mainly in DC electrification lines, contributing to a higher use of the energy returned to the grid by trains (this new technology is able to capture at least 99% of braking power), which can lead to **energy consumption savings between 7% and 15%** depending on the line and the services.
- Adding to the operator fleet new rolling stock, which uses alternative, fuels (as liquid gas or hydrogen fuel cells).

<u>3. Measures related to auxiliary systems</u>. They should take into account the incorporation of new technologies that allow decreasing the energy consumption in both the auxiliary systems on-board (as HVAC technologies or new lighting systems) and the auxiliary system of the infrastructure.

- Some estimations and models, calculate energy savings between 15% and 30%, of the auxiliary consumption, regarding new technologies of auxiliary systems implemented on board (i.e. HVAC).
- Moreover, new and more efficient point heaters, with improved insulations and regulation have yield **an average energy saving of 30%** of the auxiliary consumption (Eltherm GmbH, 2016) compared to conventional point heaters.

<u>4. Measures related to Smart Energy Management</u>. Amongst them, the following can be underlined:

- Measures related to operational procedures, for example load factor. Increasing the load factor may entail a significant reduction in energy consumption. According to García

[24] RSSB Research Project T580 - Regenerative braking on AC & DC electrified lines)

Álvarez, A. and Lukaszewicz, P. (2010), the reductions in the specific energy consumption (kWh/seat.km) may vary between **14.48% and 17.09%** depending on the type of train and service.

- Measures related to driving styles, by either the introduction of ECO-Driving Systems or due to the driver´s knowledge of the existing differences of the driving techniques, depending on if the trains has regenerative brake or not. The benefits from implementation of a driving advisory system DAS include reductions in energy consumption by avoiding unnecessary braking and running at reduced speeds. These energy consumption **reductions can reach up to 20%.**
- Introducing, in the power network, Energy Storage Systems and provide them with "intelligence" in order to manage the use of the energy. The introduction of new developments of Energy Storage Systems, as Flywheel, Supercapacitors or Batteries, may reduce the energy consumption **between 10% and 30%** depending on the system, the line and the type of service and a substantial **reduction in power peaks (50%).**
- Introducing Smart Grid technologies that allow a greater controllability of the electric loads (trains, auxiliaries…), in order to, for example, reduce power peaks in a specific area of the line. Project MERLIN[25] analyses new business models and agent interaction for the railway systems that arise when implementing a smart grid in a specific study case, the results obtained, in these specific cases analysed, show a **potential energy reductions of 11% of the imported energy.**

2.4.2 Strategies to mitigate power losses for non-traction use

2.4.2.1 Legal framework

With respect to railway non-traction energy efficiency, two EU Directives are relevant at European level and will have impacts in the next years on main energy consuming sectors and systems[26]. The two Directives are the Energy Efficiency Directive (2012/27/EU) as well as the Directive on Energy Performance of Buildings (Directive 2010/31/EU). Together they cover main energy consumers such as buildings and companies.

Directive on Energy Efficiency (2012/27/EU)

The 2012 Energy Efficiency Directive (EED) establishes a set of binding measures to help the EU reach its 20% energy efficiency target by 2020. Under the Directive, all EU countries are required to use energy more efficiently at all stages of the energy chain, from production to final consumption.

On 30 November 2016 the Commission proposed an update to the Energy Efficiency Directive, including a new 30% energy efficiency target for 2030, and measures to update the Directive to make sure the new target is met.

The Energy Efficiency Directive puts forward legally binding measures to step up Member States' efforts to use energy more efficiently at all stages of the energy chain – from the transformation of energy and its distribution to its final consumption.

First, in order to reinforce the political commitment made by the Member States in the EU 2020 Strategy the EED clearly defines and quantifies for the first time the EU energy efficiency target.

[25] MERLIN Project EC Contract No. FP7 – 314125 (2012).

[26] UIC study "Non-traction energy consumption and related CO2 emissions from the European railway sector", IZT and Macroplan, 2012

The EED also requires the Member States to set national indicative energy efficiency targets for 2020, which can be based on different indicators (primary or final energy consumption, or primary or final energy savings, or energy intensity).

The leading role of the public sector is also recognised in the provisions of the EED on public procurement, with central government required, under certain conditions, to purchase the most energy efficient products, services and buildings.

According to the Commission proposal, energy consumed in the transport sector can be excluded from the calculation of the energy savings target. However, at the same time, Member States may include transport to fulfill their obligations to achieve the overall efficiency target. In order to achieve ambitious and effective long-term energy efficiency savings, the Community of European Railway and Infrastructure Companies (CER) recommends for 2021 to 2030 that the energy used in the transport sector is included in the economy-wide target.

Directive on Energy Performance of Buildings (2010/31/EU) and Amending Directive (2010/31/EU)

This Directive concerns the residential and the tertiary sector (offices, public buildings, etc.) and is the main legislative instrument at EU level to achieve better energy efficiency in buildings. Under the Directive, member states have to enforce minimum requirements with regards to energy performance of new and existing buildings as well as technical building systems whenever they are installed, replaced or upgraded. Additionally, certification of buildings' energy performance as well as regular inspections of boilers and air conditioning systems in buildings is required. Part of this is the setting up of energy labels for buildings, see illustration below.

Amending Directive is mainly related to long-term renovation strategies required to member States to achieve an energy efficient and decarbonised European building stock by 2050, and to technical building systems, electromobility and smart readiness indicators.

The European Commission considers railway stations to be directly covered by the provisions of the Directive on energy performance of buildings as communicated to the European Parliament. Technical buildings such as workshops are not covered by the Directive.

Energy Management Systems (ISO 50001)

Energy management in the railway companies is often performed as part of their environmental management systems. Such system could be standardized according to e.g. ISO 14001 which is already more than 15 years old. Since June 2011, a new standard focusing on energy only has seen the daylight: ISO 50001. The rising energy prices have forced the international business community to act and enforce this useful energy management system.

ISO 50001 provides public and private sector organizations with management strategies to increase energy efficiency, reduce costs and improve energy performance. The standard is intended to provide organizations with a recognized framework for integrating energy performance into their management practices. Multinational organizations will have access to a single, harmonized standard for implementation across the organization with a logical and consistent methodology for identifying and implementing improvements.

2.4.2.2 Non-traction energy consumption sources

RSSB undertook a project in 2007 to assess the potential energy savings that potentially could be generated via adjusting various aspects of the non-traction elements as part of a wider governmental and industry push for energy conservation and sustainability initiatives.

Table 2-8 Various methods of saving energy in non-traction systems across rail infrastructure

Saving Option	Description	Category	Annual energy saving (MWh)	Annual energy cost saving	Annual CO_2 reduction (kg)
S2	Improved depot heating control	1	41,300	£2.5m	18.7m
S6	Improved depot pit lighting	1	7,600-12,600	£0.5m-£0.8m	3.5m-5.7m
S14	Improved PC power management	1	11,900	£0.7m	5.5m
S15	Use of TFT monitors	1	1,100	£0.1m	0.5m
S20	LED signal lamps	3	4,500	£0.3m	2.0m
S22	Replace track circuits with axle counters	3	27,000	£1.6m	12.3m
S23	Power off AWS & TPWS between trains	3	12,000	£0.7m	5.5m
S25	Improved REB temperature control	3	1,800	£0.1m	0.8m
S26	Improved power distribution	3	2,200	£0.1m	1.0m
S30	Improved level crossing barrier control	3	9,400	£0.6m	4.3m

Non-traction energy consumption usually accounts for around 15% of the overall energy consumption for a railway system.

New innovative concepts are more focussed on assessment of real user needs and meeting adequate service quality for the railway customers. Rethinking e.g. levels for lighting, heating and ventilation and making use of ambient conditions and renewable energy sources all lead to significant energy savings on system level.

Non-traction energy consumption can be divided into the following main areas of activity:

- commercial activities: stations and concessions;
- maintenance activities: workshops, depots and service buildings;
- heating of switches;
- technical railway operation: lighting of infrastructure, signalling, telecom, traffic control and data centres;
- administration and offices.

Commercial activities: stations and concessions

This category includes lighting of stations and platforms, heating, cooling and ventilation, powered equipment like escalators and elevators, passenger information systems, shops and concessions.

The trend is that energy consumption generally is going up due to higher activity and comfort levels in this field. Legislation does exist for new buildings and major upgrades and future legislation will be even stricter.

__Maintenance activities: Workshops, depots and service buildings__

This refers to lighting, heating, cooling and ventilation, powered equipment like machines, pumps and cranes.

Energy consumption in this area is going down due to the overall improvements of energy efficiency in buildings and the reduction in numbers of workshops and depots due to improved operations. This is mainly driven by building legislation and the need to reduce operational costs.

__Heating of switches__

Energy consumption in this area is going down as the energy cost itself is a strong driver and efficiency measures have been implemented to a certain extent within the last decade. Furthermore, the rail networks are getting more productive which means that the total amount of switches is going down despite of growing traffic. In this area no legislation exists neither is it foreseen.

__Technical railway operation__

Railway operation is relevant to lighting of infrastructure, signalling, trackside equipment and level crossings, telecom systems, such as train radio, GSM-R etc., traffic control and data centres.

Energy consumption is going up due to higher activity and information levels in this field partly due to the technology shift in signalling and communication. The fast-growing activity of mobile communication also contributes to rising energy consumption. No energy legislation exists but since most of the activities in this field are safety relevant, special care is needed for implementing energy efficient solutions.

__Administration and offices__

Administrative office has consumptions due to lighting, heating, cooling and ventilation, powered equipment like escalators & elevators.

2.4.2.3 Non-traction energy efficiency measures

__Commercial activities: stations and concessions__

Energy consumption generally is going up due to higher activity and comfort levels in this field. Legislation does exist for new buildings and major upgrades and future legislation will be even stricter but currently this effect is superseded by the increasing activity level e.g. the building of “rail cities” in the bigger cities where the stations become a vital part of urban development.

The main important measures taken into account for consumption reduction are:

- Insulation of existing buildings is often rather poor which makes the improvement of insulation a top priority; it is a well-established measure with short payback time.
- Lighting in stations and platforms: LED lighting is favourable, not always from component efficiency point of view but due to the potential intelligent management of lighting level as such and the life cycle costs associated. Exchanging spotlights (halogen) to LED is normally a simple measure as the lighting concept remains untouched and only components have to be exchanged. However, heat dissipation from LED lighting can be critical and tests should validate any given lighting concept before exchange. Intelligent control and replacement of less efficient lighting has a potential saving from 10% to 40%.
- Heating and cooling: The comfort level is the main driver and temperature settings should be carefully reviewed. Optimisation of actual station designs based on system view is

needed followed by optimising the technical settings of cooling and heating systems. Measures could include heat pumps and shift of cooling agents, reduction of the losses e.g. improved insulation. Replacement of heat pumps with modern systems may lead up to 30% of energy saving; other measures, such as insulation of roofs and walls from 10% to 30% of saving.

- Powered equipment e.g. escalators, elevators, ventilation: these should be fitted or upgraded with energy efficient drives and should be intelligently controlled. Standardised solutions are available in the market but substantial potential is still to be exploited in the railways.
- Passenger information systems: Energy efficiency aspects should be taken into account for acquisition of new and upgrade of existing systems. For standard components like certain displays energy labelling could be used in the decision making process. New technologies like LED backlight displays and bi-stable displays (e.g. E-ink) exists as commercially available solutions and should be considered.
- Concessions/shops: Targets and energy audits should be built into the contracts; this can allow savings up to 20%. Energy billing should be done based on real consumption using sub-metering. Efficiency benchmarking is possible with indicators for average energy consumption per m^2 for different types of concessions (e.g. food shops, cafés/restaurants, non-food). Railway owned shops could act as show cases for successful implementation of energy efficiency measures.
- Major upgrades and new stations concepts: Radical new designs and concepts like zero-energy, sustainable stations and “cradle to cradle” stations could serve as guidelines for station developments where the energy is being produced and stored locally or transferred back to the grid.

Maintenance activities: Workshops, depots and service buildings

The trend is that energy consumption in this area is going down due to the overall improvements of energy efficiency in buildings and the reduction in numbers of workshops and depots due to improved operations. This is mainly driven by building legislation and the need to reduce operational costs. For equipment, the technological improvements in other sectors, e.g. manufacturing, is driving efficiency gains. The recommendations for this field follow to a large extent the recommendations given for stations:

- Energy audits for single workshops and depots are highly recommended since customised solutions often have to be developed taking into account significant differences in age of buildings, equipment standard and their use etc.
- Insulation of existing buildings is often rather poor which makes the improvement of insulation a top priority. It is a well-established measure with short payback time.
- Lighting in workshops and depots: The recommended solutions depend on the actual used lighting technology and the quality of light required for specific purposes. The component solutions could cover energy saving bulbs, tubes, LED and low pressure sodium lights; replacement of less efficient lighting can save from 10% to 40% of consumption. The intelligent management of lighting systems is crucial using time, ambient conditions, quality, and comfort levels as control parameters; this can save from 10 % to 30% of consumption.
- Heating and cooling: The agreed temperature level for occupational health is the main driver but temperature settings should be still reviewed or updated. Measures could include heat pumps, solar heating, and cooling agents, reduction of the losses e.g. improved insulation.

- Powered equipment e.g. cranes, pneumatics, pumps: these should be fitted or upgraded with energy efficient drives and solutions and should be intelligently controlled. Standardised solutions are available in the market to some extent and substantial potential is still to be exploited in the railways. New efficient drives and pumps plus intelligent control can provide savings from 10% to 40%.

Heating of switches

The trend is that the energy consumption in this area is going down as the energy cost itself is a strong driver and efficiency measures have been implemented. Furthermore the rail networks are getting more productive which means that the total amount of switches is going down despite of growing traffic. In this area no legislation exists neither is it foreseen.

Heating of switches: The following is a prioritised list of actions to reduce the energy consumption:

- Reduce the number of switches needed for current and future traffic demand (this has a saving potential up to 30%).
- Optimise the switch designs to reduce energy losses e.g. heat pumps and improved insulation.
- Optimise the switch control taking into account rail and ambient temperature, humidity and snow/ice forecasts.
- Upgrading of the switches should take place according to normal overhaul schedules to reduce costs.

Technical railway operation

The trend is that energy consumption is going up due to higher activity and information levels in this field partly due to the technology shift in signalling and communication i.e. the shift from relay-based to electronic technologies. The fast growing activity of mobile communication also contributes to rising energy consumption. No energy legislation exists but since most of the activities in this field are safety relevant, special care is needed for implementing energy efficient solutions.

- Lighting in marshalling yards: The recommended solutions depend on the actual used lighting technology and the quality of light required for specific purposes. Replacement with low-pressure sodium or LED lamps can lead to savings up to 40%. The intelligent management of lighting systems is crucial using time, ambient light and safety levels as control parameters, leading to savings between 10% and 30%.
- For trackside equipment the most promising energy saving measure is intelligent cooling, with potential savings between 10% and 30%. This concerns switch boxes and other IT trackside equipment, classical communication boxes, tunnel radio boxes as well as GSM-R boxes. This could be realised as ambient air cooling with or without fans, improved air flow design, shift of cooling agents as well as replacement of filters for the cooling units.
- The main energy saving measure for signalling is use of LED based light systems which is available in the market with an additional resistor to maintain the standard safety features (track circuit detection); this technology has a potential saving from 20% to 30%.
- Energy consumption for data centres is growing rapidly due to technology shift and should be managed using the developed innovative solutions for "green data centres" developed outside the railway sector. Similar requirements should be applied when out-sourcing this service. The use of "green data centres" with intelligent control has a potential saving between 25% and 50%.
- Energy efficiency aspects and requirements should be taken into account for acquisition of new and upgrade of existing equipment for signalling and telecom.

Administration and offices

Legislation does exist for new buildings and major upgrades and future legislation will be even stricter.

The main important measures taken into account for consumption reduction are:

- Insulation of existing buildings is often rather poor which makes the improvement of insulation a top priority; it is a well-established measure with short payback time.
- Lighting: LED lighting is favourable, not always from component efficiency point of view but due to the potential intelligent management of lighting level as such and the life cycle costs associated. Intelligent control and replacement of less efficient lighting has a potential saving from 10% to 40%.
- Heating and cooling: The comfort level is the main driver and temperature settings should be carefully reviewed. Replacement of heat pumps with modern systems may lead up to 30% of energy saving; other measures, such as insulation of roofs and walls from 10% to 30% of saving.

3 Identification of the degrees of freedom for the power distribution network losses reduction

Electricity is a form of energy which is particularly versatile and adaptable. It is utilized by being converted into several other forms of energy: heat, light, mechanical energy and the many electromagnetic, electronic, acoustic and visual forms which are the bases of modern telecommunications, information technology and entertainment. The flow of energy to network users' appliances gives rise to electric currents which are more or less proportional to the magnitudes of the network users' demands. As these currents flow through the conductors of the supply system, they give rise to voltage drops. The magnitude of the supply voltage for an individual network user at any instant is a function of the cumulative voltage drops on all the components of the system through which that network user is supplied, and is determined both by the individual demand and by the simultaneous demands of other network users. Since each network user's demand is constantly varying, and there is a further variation in the degree of coincidence between the demands of several network users, the supply voltage is also variable.

Electricity reaches the network user through a system of generation, transmission and distribution equipment. Each component of the system is subject to damage or failure due to the electrical, mechanical and chemical stresses which arise from several causes, including extremes of weather conditions, the ordinary processes of wear and deterioration with age, and interference by human activities, birds, animals etc. Such damage can affect or even interrupt the supply to one or two many network users. To keep the frequency constant requires the amount of running generation capacity to be matched to the simultaneous combined demand instant by instant. Because both the generation capacity and the demand are liable to hang in discrete amounts, especially in the event of faults on the generation, transmission or distribution networks, there is always a risk of a mismatch, resulting in an increase or decrease of the frequency. This risk is reduced, however, by connecting many systems into one large interconnected system, the generation capacity of which is very great relative to the changes which are likely to occur.

3.1 Power quality

The concept of power quality is defined as the capability of the electricity grid to provide customers reliable, ideal and non-tolerant electricity. In details power quality issues can be classified into several levels. The interest in power quality is related to all three parties concerned with the power i.e. utility companies, equipment manufactures and electric power consumers. Understanding power quality can be confusing at best. There have been numerous articles and books concerning power quality. There are two terms known in power systems about the quality of power: Good power quality and poor power quality. Good power quality can be used to describe a power supply that is always available, always within the voltage and frequency tolerances and has a pure noise-free sinusoidal wave shape to all equipment because most equipment was designed on that basis. Unfortunately, most of equipment that is manufactured also distorts the voltage on the distribution system, leading to what is known as poor power quality. The cost of power quality issues can be very high and include the cost of downtimes, loss of customer confidence and in some cases, equipment damage. Indeed, power quality is an important point in the relationship between suppliers and consumers but might become a contractual obligation that steer on improving voltage quality, availability, performance and efficiency and these improvements will have: benefits for industrial customers and for suppliers utilities[27].

It is obvious that power quality is an important characteristic of today's distribution power systems. Sensitive equipment and non-linear loads are now more commonplace in both the industrial sectors and the domestic environment. From years ago, researchers have been working on various kinds of filters and devices to enhance the overall power quality of power system, but today the nature of distribution system has been changed and power electronic based DGs play an important role in distribution grids. An example of these potentially pollutants is inverter-based DGs such as Solar panels, which use power electronic devices as an interface to connect to the grid. By the increasing penetration of DGs in today's grid, power quality issues become more important and paying attention to this topic is inevitable.

3.1.1 Classification and Impact of Power Quality Phenomena

To make the study of Power Quality useful, the various types of disturbances need to be classified by magnitude and duration[28].

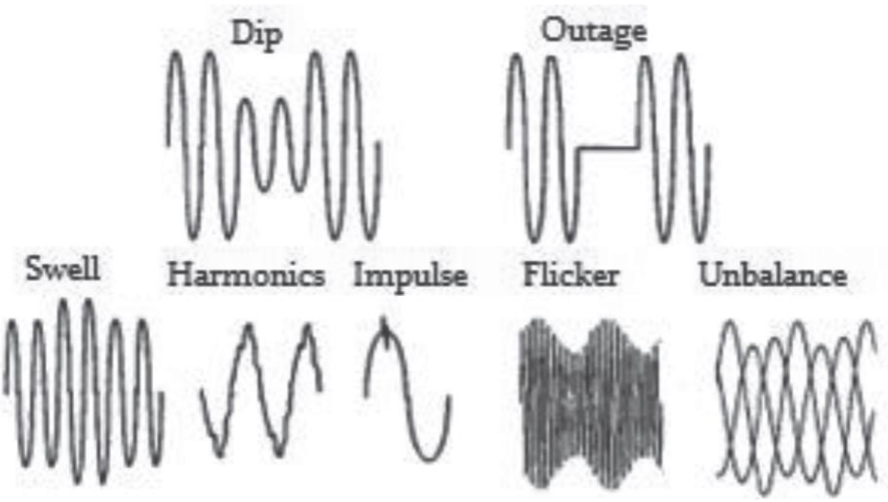

Figure 3-1 Different Problems encountered of Power Quality

3.1.1.1 Voltage Dips

It is defined as temporary reduction of the RMS voltage at a point in the electrical supply system below a specified start threshold. Short duration under-voltages are called "Voltage Sags" or "Voltage Dips [IEC]". Voltage sag[29] is a reduction in the supply voltage magnitude followed by a voltage recovery after a short period of time. The major cause of voltage dips on a supply system is a fault on the system,

27

R.C. Sermon, "An overview of power quality standards and guidelines from the end-user's point-of-view," in *Proc. Rural Electric Power Conf.*, pp. 1-15, May 2005..

28 Agarwal A, Kumar S, Ali S. A research review of power quality problems in electrical power system. MIT Int J Electr Instrum Eng 2012;2:88 - 93.

29 A. Domijan, G.T. Heydt, A.P.S. Meliopoulos, S.S. Venkata, S. West, "Directions of research on electric power quality," *IEEE Transactions on Power Delivery*, Vol. 8, pp. 429-436, 1993.

i.e. sufficiently remote electrically that a voltage interruption does not occur. Other sources are the starting of large loads and, occasionally, the supply of large inductive loads. The impact on consumers may range from the annoying (non-periodic light flicker) to the serious (tripping of sensitive loads and stalling of motors).

3.1.1.2 Under Voltages

Excessive network loading, loss of generation, incorrectly set transformer taps and voltage regulator malfunctions, causes under voltage. Loads with a poor power factor or a general lack of reactive power support on a network also contribute. Under voltage can also indirectly lead to overloading problems as equipment takes an increased current to maintain power output (e.g. motor loads).

3.1.1.3 Voltage Surges/Spikes

Voltage surges/spikes are the opposite of dips – a rise that may be nearly instantaneous (spike) or takes place over a longer duration (surge). These are most often caused by lightning strikes during switching operations on circuit breakers/contactors (fault clearance, circuit switching, especially switch off of inductive loads).

3.1.1.4 Voltage Swell

Momentary increase of the voltage, at the power frequency, outside the normal tolerances, with duration of more than one cycle and typically less than a few seconds. The main causes are Start/stop of heavy loads, badly dimensioned power sources, badly regulated transformers (mainly during off-peak hours).Consequences is data loss, flickering of lighting and screens, stoppage or damage of sensitive equipment, if the voltage values are too high[30] .

3.1.1.5 Voltage fluctuation

Oscillation of voltage value, amplitude modulated by a signal with frequency of 0 to 30 Hz. Causes are arc furnaces, frequent start/stop of electric motors (for instance elevators), oscillating loads. Consequences are most consequences are common to under voltages. The most perceptible consequence is the flickering of lighting and screens, giving the impression of unsteadiness of visual perception.

3.1.1.6 Voltage Unbalance

A voltage variation in a three-phase system in which the three voltage magnitudes or the phase angle differences between them are not equal. Causes are large single-phase loads (induction furnaces, traction loads), incorrect distribution of all single-phase loads by the three phases of the system (this may be also due to a fault). Consequences are Unbalanced systems imply the existence of a negative sequence that is harmful to all three phase loads. The most affected loads are three-phase induction machines.

[30] Bollen, M. , "Understanding Power Quality Problems – Voltage Sags and Interruptions", IEEE Press Series on Power Engineering – John Wiley and Sons, Piscataway, USA (2000).

3.1.1.7 Harmonic distortion

Voltage or current waveforms assume non-sinusoidal shape. The waveform corresponds to the sum of different sine-waves with different magnitude and phase, having frequencies that are multiples of power-system frequency. Main Causes are Classic sources: electric machines working above the knee of the magnetization curve (magnetic saturation), arc furnaces, welding machines, rectifiers, and DC brush motors. Modern sources: all non-linear loads, such as power electronics equipment including ASDs, switched mode power supplies, data processing equipment, high efficiency lighting. Consequences are increased probability in occurrence of resonance, neutral overload in 3-phase systems, overheating of all cables and equipment, loss of efficiency in electric machines, electromagnetic interference with communication systems, and errors in measures when using average reading meters, nuisance tripping of thermal protections. Improving the harmonics on the network will improve the losses, however the energy associated with the equipment operation to improve harmonics is potentially greater than the value gained through improvement in network losses.

3.1.2 Causes of Power Quality problems

In today's fast-paced environments, a huge amount of money is spent on sate of the art computer controlled equipment and systems. The computer industry is the biggest user of semiconductor devices, and power electronics devices which in some extent are more likely to generate the distorting harmonics. These harmonics can cause power to be used inefficiently and can be a source of premature equipment failure which cause owners, industrial companies and investors a great deal of frustration and disappointment and in many cases, result in a great loss of time and money, and that lead us to ask a valuable question "What is the problem?" But whatever the answer is, Chapman[31] has classified them as a power quality problems and the latter is subdivided into two categories:

- Supply system quality problems.
- Installation and load related problems.

3.1.2.1 Supply System Quality Problems

- Supply interruption
- Transient interruption
- Transients
- Under voltage/over voltage
- Voltage dip/voltage surge
- Voltage imbalance
- Flicker
- Harmonic distortion

These problems can be classified into one of three disturbance categories based upon duration [6]: Transient disturbances include unipolar Transients, oscillatory transients (such as Capacitor switching), and localised milliseconds. Transients can originate internally within the building or externally on utility power lines. They represent about 12 to 15% of all power line problems. Momentary disturbances are

[31] David Chapman, "Electrical design—A good practice guide", CDA Publication 123, Dec. 1997.

voltages increases or decreases (sags, swells, and interruptions) lasting more than 10 milliseconds but less than three seconds. The majority of voltage sags result on utility lines from faults on the distribution or transmission lines and they represent about 60% of all power problems. Voltage swells are the least frequent of the Power line problems representing about 2 to 3% of all power problems according to industry studies. Steady-state disturbances are voltage increases or decreases (under voltages, over voltages, and interruptions). Interruptions and power outages can originate from electrical short circuits in Building wiring or on utility power lines. These interruptions will cause electrical, computer and electronic equipment shut down and losses in operations and revenues. Local energy storage systems can be used to protect sensitive production equipment from shutdowns caused by voltage sags or momentary interruptions. These are usually DC storage systems, such as UPS, batteries, superconducting magnet energy storage (SMES), storage capacitors etc. The output of these devices is supplied to the system through an inverter on a momentary basis by a fast acting electronic switch. Enough energy is fed to the system to replace the energy that would be lost by the voltage sag or interruption.

3.1.2.2 Installation and Load Related Problems

The major problems in this category can be classified in one of the three following groups:

- Harmonic currents
- Earth (Ground) leakage currents
- Voltage dips and transients

Harmonic currents will cause wiring, motors and transformers to overheat. The result may be a breakdown of insulation and a significant reduction of equipment lifespan. All non-linear loads generate harmonics. This includes all loads, which use switching to control or convert power. The principal design consideration for an earthling system is that it must protect people and animals from receiving potentially fatal electric shocks in the event of a fault condition. Now, earth conductors are carrying large leakage current permanently as well as serving as a sink for high frequency noise currents. If for any reason the connection to earth is poor, then the impedance of the primary earth route will be high and earth Leakage currents will seek alternative routes to earth. This may result in current flowing in unexpected places with consequent risk should the system be disconnected. Heavy loads such as air conditioning systems, large motors during the starting process, principally cause Dips. However, flat topping is caused by electronic equipment such as the start -up of printers. The combination of surges and dips in the voltage lead to what is known as voltage Flicker and this latter is caused by the operation of large cyclic loads and can reduce the life of motors drives and electrical contacts. In Table 3-1, the main sources, causes and effects of electrical Power Quality problems has been summarized[32].

Table 3-1 Main sources, causes and effects of electrical power quality

Phenomena	Causes	Effects
Harmonics	Electromagnetic interference from appliances, machines, radio and TV broadcasts.	Continuous distortion of normal voltage, Random data errors.
Voltage Sags/ Swells	Major equipment start up or shut down, Short circuits (faults), Undersized	Memory loss, Data errors, Dim or bright lights, Shrinking

[32] Marty Martin, “Common power quality problems and best practice solutions,” Shangri-la Kuala Lumpur, Malaysia 14. 1997.

	electrical wiring, Temporary voltage rise or drop.	display screens, Equipment shutdown
Interruption	Switching Operator, Attempting to isolate electrical problem and maintain power to power distribution area.	Equipment trips off, Programming is lost, Disk drive crashes.
Flicker	Arc furnace, Voltage fluctuations on utility transmission and distribution systems.	Visual irritation, introduction of many harmonic components in the supply power and their associated equipment.
Transient	Lightning, Turning major equipment on or off, Utility Switching.	Tripping, Processing Errors, data loss, Burned circuit boards.

3.1.3 Standards on Power Quality

There are IEEE and IES standards[33] such as IEC 61000-3-6, EN50160, and IEEE 519-1992 about power Quality. Nevertheless, IEEE standards do not provide structured and comprehensive discussions on power quality in comparison to IEC standards, but IEEE and IEC both have standards for this special topic, and it is a proof to the importance of power quality issues in modern power systems. In both IEEE and IEC, the ultimate goal of harmonic control is to ensure voltage quality. However, IEEE and IEC approach the issue of allocating customer harmonic current production differently. In this section, we will look at standard EN50160 (BS EN 50169:2010+A1:2015) 'Voltage characteristics of electricity supplied by public electricity networks' for definition and limits in distribution network in Europe. This European Standard defines where possible the variations of the characteristics normally to be expected. In other cases, the standard provides the best possible indication of what, in quantitative terms, is to be expected. This standard deals with the voltage characteristics in statistical or probabilistic terms. It is in the economic interests of the network user that the standard of supply should relate to normally expected conditions rather than to rare contingencies, such as an unusual degree of coincidence between the demands of several appliances or several network users.

3.1.4 EN50160 (BS EN 50169:2010+A1:2015) 'Voltage characteristics of electricity supplied by public electricity networks'

The object of this European Standard is to define, describe and specify the characteristics of the supply voltage concerning: a) Frequency; b) Magnitude; c)Waveform; d)Symmetry of the line voltages.

These characteristics are subject to variations during the normal operation of a supply system due to changes of load, disturbances generated by certain equipment and the occurrence of faults which are mainly caused by external events. The characteristics vary in a manner which is random in time, with reference to any specific supply terminal, and random in location, with reference to any given instant of time. Because of these variations, the values given in this standard for the characteristics can be expected to be exceeded on a small number of occasions. Some of the phenomena affecting the voltage are particularly unpredictable, which make it very difficult to give useful definite values for the corresponding characteristics. The values given in this standard for the voltage characteristics associated with such phenomena, e.g. voltage dips and voltage interruptions, shall be interpreted accordingly. The following referenced documents are indispensable for the application of this

[33] Halpin SM. Comparison of IEEE and IEC harmonic standards. In: IEEE power engineering society general meeting, vol. 3; 2005. p. 2214-6.

document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

Table 3-2 Reference list

Standard	Year	
EN 60664-1	2007	Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests (IEC 60664-1:2007)
EN 61000-3-3	2008	Electromagnetic compatibility (EMC) – Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection (IEC 61000-3-3:2008)
EN 61000-4-30	2009	Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods (IEC 61000-4-30:2008)
IEC 60364-5-53+A1	2002	Electrical installations of buildings – Part 5-53: Selection and erection of electrical equipment – isolation, switching and control
IEC/TR 61000-2-8	2002	Electromagnetic compatibility (EMC) – Part 2-8: Environment – Voltage dips and short interruptions on public electric power supply systems with statistical measurement results
IEC/TR 61000-3-7	2008	Electromagnetic compatibility (EMC) – Part 3-7: Assessment of emission limits for fluctuating loads in MV and HV power systems

3.1.5 Low, Medium and High voltage supply characteristics

Low voltage (LV) is defined as voltage whose nominal RMS value is less than 1 kV. Medium voltage (MV) is defined as voltage whose nominal RMS value is between 1 kV & 36 kV. High voltage (HV) is defined as voltage nominal RMS value between 36 kV and 150 kV. Because of existing network structures, in some countries the boundary between MV and HV can be different. Network users with demands exceeding the capacity of the LV network are generally connected to networks at nominal voltages above 1 kV. Under normal operating conditions excluding the periods with interruptions, supply voltage variations should not exceed ± 10 % of the nominal voltage in general. In cases of electricity supplies in networks not interconnected with transmission systems or for special remote network users, voltage variations should not exceed + 10 % / - 15 % of nominal voltage. Network users should be informed of the conditions.

3.1.5.1 Rapid Voltage Changes

Rapid voltage changes of the supply voltage are mainly caused either by load changes in the network users' installations, by switching in the system, or by faults. If the voltage during a change crosses the voltage dip and/or the voltage swell threshold, the event is classified as a voltage dip and/or swell rather than a rapid voltage change. More information is given in EN-61000-3-5 & EN61000-2-12. A change of the voltage rms value within ± 10 % of the agreed voltage level and which occur more rapid than 0,5 % of the agreed voltage level per second. A voltage change characteristic is the time function of the rms voltage change evaluated as a single value for each successive half period between zero-crossings of the source voltage between time intervals in which the voltage is in a steady state condition for at least 1 second. The voltage is in a steady state condition when the rms value is in between ± 0,5 % of the agreed voltage rms level.

3.1.5.2 Flicker Severity

Voltage fluctuation cause changes of the luminance of lamps which can create the visual phenomenon called flicker. Above a certain threshold flicker becomes annoying. The annoyance grows very rapidly with the amplitude of the fluctuation. At certain repetition rates even very small amplitudes can be annoying. Under normal operating conditions, during each period of one week the long term flicker severity caused by voltage fluctuation should be less than or equal to 1 for 95 % of the time. Reaction to flicker is subjective and can vary depending on the perceived cause of the flicker and the period over which it persists. In some cases flicker as 1 gives rise to annoyance, whereas in other cases higher levels of flicker are noticed without annoyance. In the case of complaints, the HV limit and appropriate HV, MV and LV mitigation measures shall be chosen in such a way that at LV the flicker values do not exceed 1.

3.1.5.3 Supply Voltage unbalance

Under normal operating conditions, during each period of one week, 95 % of the 10 min mean RMS values of the negative phase sequence component (fundamental) of the supply voltage shall be within the range 0 % to 2 % of the positive phase sequence component (fundamental). In some area, unbalances up to 3% at three-phase supply terminals occur in some area. In this European Standard only values for the negative sequence component are given because this component is the relevant one for the possible interference of appliances connected to the system.

3.1.5.4 Harmonic Voltage

Sinusoidal voltage with a frequency equal to an integer multiple of the fundamental frequency of the supply voltage. Harmonics of the supply voltage are caused mainly by network users' non-linear loads connected to all voltage levels of the supply network. Harmonic currents flowing through the network impedance give rise to harmonic voltages. Harmonic currents and network impedances and thus the harmonic voltages at the supply terminals vary in time. Under normal operating conditions, during each period of one week, 95 % of 10 min mean RMS values of each individual harmonic voltage shall be less than or equal to the values given in the standard. Resonances may cause higher voltages for an individual harmonic. Moreover, the THD of the supply voltage (including all harmonics up to the order 40) shall be less than or equal to 8 % 5 % as a mean value over 10 min and one week respectively for 100 % of the time at all supply terminals. The limitation to order 40 is conventional. Depending on the type of voltage transformer used, the measurement of higher order harmonics may be not reliable; further information is given in EN 61000-4-30:2009, A.2.

3.1.5.5 Supply voltage dips/swells; measurement and detection

Voltage dips are typically originated by faults occurring in the public network or in network users' Installations. Voltage swells are typically caused by switching operations and load disconnections. Both phenomena are unpredictable and largely random. The annual frequency varies greatly depending on the type of supply system and on the point of observation. Moreover, the distribution over the year can be very irregular.

If statistics are collected, voltage dips/swells shall be measured and detected according to EN 61000-4-30, using as reference the nominal supply voltage. The voltage dips/swells characteristics of interest for this standard are residual voltage (maximum RMS voltage for swells) and duration. On LV networks, for four-wire three phase systems, the line to neutral voltages shall be considered; for three-wire three phase systems the line to line voltages shall be considered; in the case of a single phase connection, the supply voltage (line to line or line to neutral, according to the network user connection) shall be considered.

Conventionally, the dip start threshold is equal to 90 % of the nominal voltage; the start threshold for swells is equal to the 110 % of the nominal voltage. The hysteresis is typically 2 %; reference rules for hysteresis are given in 5.4.2.1 of EN 61000-4-30:2009.

3.1.5.6 Power Frequency

The nominal frequency of the supply voltage shall be 50Hz (in all European countries). Under normal operating conditions the mean value of the fundamental frequency measured over 10 seconds shall be within a range of:

- For systems with synchronous connection to an interconnected system:
  - 50Hz ±1 % (i.e. 49.5 Hz …. 50.5 Hz) during 99.5% of a year
  - 50Hz ±4 % / -6 % (i.e. 47 Hz… …. 52 Hz) during 100 % of the time
- For systems with no synchronous connection to an interconnected system (e.g. supply systems on certain islands)
  50Hz ±2 % (i.e. 49 Hz …. 51 Hz) during 95% of a weak
  50Hz ±15 % (i.e. 42.5Hz… 57.5 Hz) during 100 % of the time

Frequency variations that are large enough to cause problems are most often encountered in small isolated networks, due to faulty or maladjusted governors. Other causes are serious overloads on a network, or governor failures, though on an interconnected network, a single governor failure will not cause widespread disturbances of this nature.

3.1.6 Voltage & frequency regulation in UK

The Distribution Code requires that the system be designed to enable the normal operating frequency supplied to customers to comply with the Electricity Safety, Quality and Continuity (ESQC) Regulations 2002. The Regulations require to declare a frequency of 50Hz for the supplies, and allow a variation not exceeding one per cent above or below the declared frequency. Currently, distribution systems are reliant on the National Grid Electricity System Operator (NGESO) to maintain frequency in accordance with the Grid Code, which requires the frequency of the transmission system to be controlled within the limits of 49.5 – 50.5Hz unless exceptional circumstances prevail. Additional performance requirements of users are given in section CC6.1.3 and ECC6.1.3 of the Grid Code.

The distribution system operates at the following nominal voltages: 132kV, 66kV, 33kV, 20kV, 11kV, 6kV and 5.75kV or 400/230V. 6kV and 5.75kV are non-preferred legacy voltages.2

The Distribution Code requires that the distribution system, and any user connections to it, be designed to enable the voltages supplied to customers to comply with statutory regulations. The regulations require us to declare the voltage at which the supply is delivered to connected customers. The distribution system is designed such that the voltage at all points where customers' premises are connected lies within statutory limits set out in Table 3-3 below.

The distribution system is designed to enable the voltage at the lower voltage levels of a transformer to be maintained in accordance with the principles of Engineering Recommendation P10 - Voltage control at bulk supply points - for the specified operating scenarios.

The voltage at the source substation 132kV, 66kV, 33kV, 20kV and 11kV busbars will normally be held constant by means of automatic voltage regulator controlling the tap changers of the transformers feeding that busbar. Voltage control systems at the different transformation levels are time-graded to minimise the number of tap-changer operations. Tap changing facilities at 20/0.433kV and 11/0.433kV transformers are typically only suitable for operation when de-energised. Under the terms of the Grid Code, the NGESO may, under certain circumstances instruct us to reduce demand on the distribution system; this is normally achieved by blanket voltage reductions applied remotely to the 20kV and 11kV distribution systems.

Table 3-3 Distribution system statutory voltage limits in UK

Nominal Voltage	Voltage limit
230/400 V	+10%/-6 %
11kV, 20 kV, 33kV, 66kV	±6%
132kV	±10%

3.2 Smart Grid Vision and Roadmap

The European Union faces major challenges concerning climate change, security of energy supply and the need to increase market competitiveness. Energy demand is steadily increasing and dependence on fossil fuels from outside the European Union is growing at the time of fiercer competition on the global energy markets, inevitably pushing up energy prices. The main factor driving the underlying growth in energy demand is economic growth. A smart electricity grid opens the door to new applications with far-reaching impacts: providing the capacity to safely integrate more renewable energy sources (RES), electric vehicles and distributed generators into the network; delivering power more efficiently and reliably through demand response and comprehensive control and monitoring capabilities; using automatic grid reconfiguration to prevent on restore outages (self-healing capabilities); enabling consumers to have greater control over their electricity consumption and to actively participate in the electricity market.[34] In this context, at distribution system level, the increasing requests for connection of solar PV installations, onshore wind farms, and other forms of distributed generation are creating technical challenges, which have knock-on impacts for the transmission system as well. In addition, customers increasingly become prosumers (both consuming and producers of electricity) and it requires to facilitate a fair market for the services that could provide to the electrical network. The network evolution has already started, key enabling technologies are commercially available and have already been trialled on the network. These technologies have allowed customers to get connected to the network quickly; where previously they would have had to wait on significant reinforcement works in order to connect. All of this will occur in a context in which

[34] Smart Grid Task Force Mandate. Brussels : European Commission, 2011.

policy makers are promoting greater competition and creating new markets for energy balancing services. Customers will become more empowered and benefit from having access to more information and greater choice.

A smart grid could provide a range of benefits and opportunities for consumers, businesses, network operators and the wider energy industry, both day-to-day and in our transition to a low carbon economy. These benefits include:

- Reduced cost to consumers through saving on network costs
- Supporting economic growth and jobs
- Increased energy security and integration of low carbon technologies

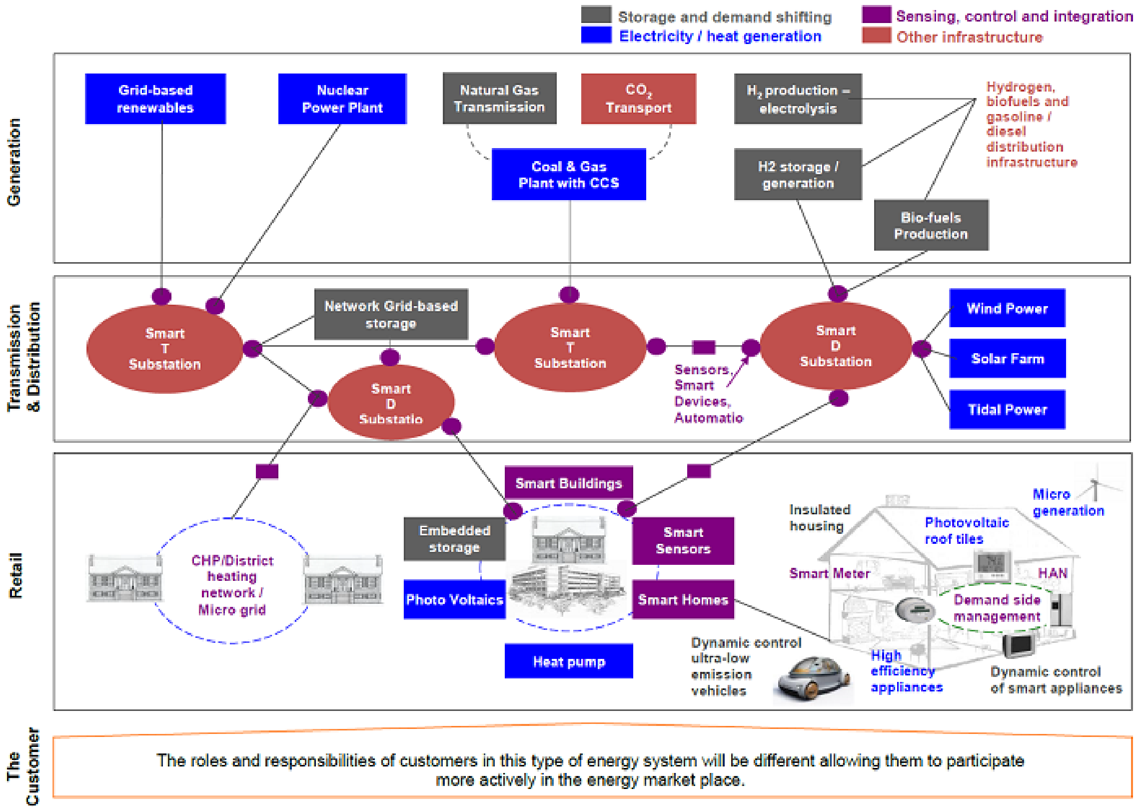

Figure 3-2 Role and relationship between elements of the smart grid

The smart Grid Forum's vision for example in Great Britain is[35]:

The first phase of smart grid deployment is focused on capturing the short-term benefits of deploying smart technologies and solutions, whilst also preparing for the accelerated deployment of distributed generation and increasing electrification of heating and transport projected to take place in the 2020s.

During this phase, network companies build on the success of the Low Carbon Network Fund trials to move from participating in trials to integrating successful pilots into business as usual activities. In parallel, changes in regulatory and commercial frameworks to support demand side management and

35 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/285417/Smart_Grid_Vision_and_RoutemapFINAL.pdf

storage are made, as are provisions that support DSO access to smart meter data while safeguarding consumer privacy.

The second phase of smart grid deployment sees a much greater role for the consumer, following the successful roll-out of smart meters across Great Britain.

Consumers view the visibility and control they have over their energy use as routine, and this contributes to the further development of the smart appliances industry. Increasingly, community energy groups and local authorities look to develop local sources of renewable energy to reduce costs, increasing the trend towards decentralised energy development. The increasing electrification of heat and transport and more distributed generation, increase the need to balance the electricity system at local levels.

The third phase will see GB achieve its vision objectives, where a smart grid enables GB to develop a fully integrated smart energy system and a platform for the further development of technologies to support the increasing electrification of the heating and transport sector as well as smarter homes and businesses. These developments are also contributing to the evolution of smart cities.

Figure 3-3 Key stages in the development of a smart grid

Finally the Future Power System Architecture (FPSA) project[36] commissioned jointly by DECC (now BEIS) and Ofgem and completed by the IET and Energy Systems Catapult outlines some of the key future uses of the UK network and the challenges of realising this network. The report highlights seven key drivers of *'new or significantly extended functionality':*

1. **'The flexibility to meet changing but uncertain requirements** recognising that the form, magnitude, timing and tipping points of future power system developments are not all predictable far in advance. Changes include uptake of new technologies (e.g. domestic generation and storage, electric vehicles, heat pumps) or active consumer participation (e.g. smart tariffs, home energy automation).

[36] http://www.theiet.org/sectors/energy/resources/fpsa-project.cfm?origin=reportdocs

2. **The change in mix of electricity generation** will require new techniques to manage system frequency, stability and reliability as intermittent renewable sources and distributed generation grow to take up a much larger share of total generation.

3. **The use of price signals or other incentives will enable customers to save money by becoming active participants in the power sector** and, in doing so, to contribute to decarbonisation while keeping system balancing costs down.

4. **The emergence of new participants such as smart cities, groups of technology users, aggregators and social enterprises** will require new modes of interaction with the power system to exploit benefits of aggregation while mitigating any risks of destabilisation.

5. **The active management of networks, generation, storage and demand** will facilitate growth of intermittent and distributed generation and new loads such as heat pumps and electric vehicles, without unnecessary network constraints or costly upgrades.

6. **The recovery from major outages will be far more challenging as the power system becomes more decentralised.** Managing prolonged outages will require sophisticated coordination to reintroduce load and to reconnect distributed generation and storage.

7. **The need for some coordination across energy vectors** (electricity, gas, biofuels, petroleum and heat networks) will become inevitable as the UK decarbonisation strategy proceeds with the electrification of heat and transport energy.'

In summary, key capabilities of the smart grid system include the integration and aggregation of (i) distributed energy resources (distributed generation-DG, electric vehicle-EV), (ii) demand response (DR) and (iii) large-scale renewable energy sources (RES). System integration is crucial to enable these capabilities. Making the smart grid system work requires the cooperation and integration of multidisciplinary players with different business interest and the adoption of new compatible business models and regulations. Moreover, it is important to make sure that consumers are on board as the extent of smart grid transformation should be tailored to consumers' needs and to their willingness to pay for its implementation.

3.3 Electric Vehicles and Smart Grid integration

The concept goal of the smart grid along with the future deployment of the EVs puts forward various challenges in terms of electric grid infrastructure, communication and control. On the other hand, the electrification of transportation sector appears to be one of the feasible solutions to the challenges such as global climate change, energy security and geopolitical concerns on the availability of fossil fuels. The EVs are potential on serving the electric grid as independent distributed energy source. It has been revealed by some studies that most vehicles are parked almost 95% of their time. In this case, they can remain connected to grid and be ready to deliver the energy stored in their batteries under the concept of vehicle to grid (V2G) introduced earlier by Kempton[37]. To this end, the EV technology can provide the grid support by delivering the ancillary services such as peak power shaving, spinning reserve, voltage and frequency regulations whenever needed. Besides, the integration of large renewable energy sources (RES) like wind and photovoltaic (PV) solar energies into the power system has grown up recently. These RES are intermittent in nature and their forecast is quite unpredictable. The penetration of the RES into the power market is enormously increased to meet the stringent energy policies and energy security issues.

[37] Kempton W, Letendre S. Electric vehicles as a new power source for electric utilities. J Transp Res Part D 1997;2(3):157–75.

China for the year 2020 has set a goal to install 150–180 GW of wind power and 20 GW of PV solar power. This huge penetration of the RES into power system will require large energy storage systems (ESS) to smoothly support electric grids so that the electrical power demand and operating standards are met at all the times[38]. In this case, the EV fleets are the possible candidate to play a major role as the dynamic energy storage systems using the V2G context. To this point, the EVs can be aggregated and controlled under the virtual power plant (VPP) concept model. While the EVs are providing these opportunities through charging and discharging of their battery packs, a number of challenges are imposed to the power system grid. These challenges compel the changes on the planning, operation and control of the electric grid. To the utility, the EVs are both the dynamic loads which are difficult to schedule but also a potential back up for the electric grid. Similarly, the vehicle owners have some notion that possessing an EV will substantially increase an extra operating cost when compared to owning an internal combustion engine vehicle (ICEV). Hence, an attractive scenario is needed to merge them so that a sharing of load can be realized between the two parties.

However, as the majority of the people witness and become aware of the contemporary penetration of the EVs, they would require knowing how much it costs for recharging their vehicles and find a way to minimize charging costs similar to their usual ICEV refuelling practice. On the other hand, a cost for selling power to the grid should instantaneously be known by the vehicle owners or EVs fleet operator/aggregator in the case of providing V2G services. Furthermore, the aggregator has to know in real time the characteristic parameters (i.e. driving patterns, state of charge, total capacity, etc.) of the aggregated EVs for the network management response such as demand side management issues, frequency regulation and other ancillary services[39]. Definitely, this demonstrates how the EVs would change the way we daily understand and interact with the electric grid. The cost of electricity will be sensitive and determinant factor for the EV owners or energy market players to interact with the grid while the load profile will dictate on the grid operator (GO) side. With the deregulated power market, the real-time-pricing scenario is quite intuitive, but it requires advanced metering, information and communication control systems. This is shifting the existing grid to the future electric grid network mostly referred to as smart grid where the EVs as dynamic loads and potential energy buffer (i.e. dynamic ESS) can be accommodated. In the smart grid infrastructure, the real-time pricing and communication are conceivable through smart metering and advanced information and communication technology (ICT)[40]. Intelligent scheduling of the EV charging is also attainable to relieve the stresses on the power distribution system facility. These mutual relationships between the EVs and smart grid make a perfect match for a modern power system model. To this end, a real time-advanced communication is a vital ingredient for the information exchange especially pricing, energy forecast and EV-driving characteristics among parties. Hence to successfully operate this scenario, the smart grid platform is indispensable. In smart grid implementation, an advanced communication infrastructure can be easily accessed and make it a potential moving target for the EV penetration into the energy market.

[38] International Electrotechnical Commission (IEC). Grid integration of large capacity renewable energy sources and use of large-capacity electrical energy storage. White paper 3; 2012.
[39] Ortega-Vazquez MA, Bouffard F, Silva V. Electric vehicle aggregator/system operator coordination for charging scheduling and services procurement. IEEE Trans Power Syst 2013;28(2):1806–15.
[40] Gungor VC, et al. A survey on smart grid potential applications and communication requirements. IEEE IEEE Trans Ind Inform. 2013;9(1):28–42.

3.3.1 EV charging and electric grid interaction

EV charging is one of the fundamental schemes in the electric vehicles' applications. There are several charging levels for EVs that reflect the power capability and charging duration. These levels have been standardized to reveal the EV slow or fast charging scenarios. The slow charging (typically up to 8 h-PHEV or 20 -BEV) can be experienced at home or office areas whereas the fast charging (typically 15 min to 1 h) at dedicated charging stations in commercial or public places. With the current EV battery technology such as 24 kWh battery pack for Nissan Leaf, to recharge an EV will consume power almost the same as a single household in Europe or US per day. When two or three EVs are connected for charging purposes, there is a proportional growth of the energy usage. Hence, it reflects the increase in the consumption capacity to the existing grid infrastructure. A study surveyed various issues regarding the electrification of the transport sector[41]. They include the policies to foster the EV adoption, charging infrastructures and standards. The study reported that the 3.3 kW charger used at 220 V/15 A would increase the current demand of the household by 17–25%. Different charging schemes have been discussed recently regarding the driving patterns of the vehicle owner and existing grid model. These schemes include uncontrolled (dumb) charging, dual tariff charging and smart or intelligent charging. In uncontrolled charging scheme, an EV starts charging immediately when connected to the electric power. Numerous studies have been conducted to assess the impact of this type of charging approach on the power system networks[42] . Almost all studies concluded that this kind of charging increases the overloading and investment cost of the power distribution system. If this additional load is not appropriately controlled, it can result to further aging of the power system equipment and tripping of the relays under rigorous overload conditions. It is reported that up to 60–70% of the required incremental investment cost in the distribution system facility can be circumvented if the EV smart charging schemes are adopted. Similarly, one of the mitigations used to safely operate the distribution system while accommodating the large size of the EVs penetration is by shifting this extra load to a valley period or to optimize the available power using the coordinated charging schemes. In this case up to 5–35% of the essential investment cost have been reported to be avoided by load shifting practice with the energy losses up to 40% of the actual values[43].

3.3.2 EVs with V2G system architecture

Electric vehicles can be integrated into power systems and operate with different objectives such as the dynamic loads by drawing power from the grid (during charging) or dynamic ESS by feeding power to the electric grid. It is worth mentioning that the latter is referred to as vehicle to grid (V2G). The limited EVs as resources, their spatial-location and low individual storage capacity make them unrealizable for the V2G services. In this case, a large number of EVs are aggregated in different ways depending on the control schemes and objectives to realize the V2G concept[44]. The aggregation of the EVs as a single controllable distributed energy source can participate in energy market for supporting electric grid in regulation and system management. The interaction of EV with smart grid can realize

[41] Boulanger AG, Chu AC, Maxx S, Waltz D. Vehicle electrification: status and issues. Proc IEEE 2011;99(6):1116–38.

[42] Waraich R, et al. Plug-in hybrid electric vehicles and smart grids: investigations based on a microsimulation. Transp Res Part C 2013;28:74–86.

[43] Fernandez LP, Roman TGS, Cossent R, Domingo CM, Frias P. Assessment of the impact of plug-in electric vehicles on distribution networks. IEEE Trans Power Syst 2011;26(1):206–13.

[44] Sortomme E, El-Sharkawi MA. Optimal scheduling of vehicle-to-grid energy and ancillary services. IEEE Trans Smart Grid 2012;3(1):351–9.

V2G services through bidirectional power flow or unidirectional power flow. The former means the electric power can flow from the vehicle to grid (V2G) and the grid can send power back to the EV at the time of charging. Most of the literatures have investigated the economics and feasibility of this mutual interaction between the grid and aggregated EVs[45] . Extensive safety protection measures such as anti-islanding and system cost are among the demerits reported to reduce full benefits of this system architecture. On the other side, the unidirectional configuration offers power flow in only one direction, from the grid to EV (only to charge the battery but not to discharge it)[46]. Studies have shown that in this configuration, the EVs can participate in the energy market and provide ancillary services like frequency and voltage regulation. With issues like protection and metering systems, the extra revenue earned by the bidirectional power flow architecture can be nullified to negative. It is concluded that almost all the V2G benefits acquired by using bidirectional power flow can also be achieved by adopting unidirectional power flow. Further studies are however required to demonstrate the viability of the unidirectional power flow over its counterpart in the areas such as lower power capacity for the V2G transactions. Meanwhile, the conceptual framework of the VPP offers an aggregation scenario that eases control and information exchange between the utility entity (control center) and the EV fleet to facilitate the V2G realization. Different schemes of the VPP frameworks in the V2G context can be modelled depending on the control philosophy and aggregation type to meet the grid and EVs integration challenges. The control approach in the VPP can be centralized, hierarchical or distributed. In centralized control scheme the decision making and data exchange are based on the VPP central control center (VPPC) while in the distributed control scheme the decisions and flow of information are fully achieved in the distributed manner. On the other hand, the hierarchical scheme includes some decision making and information exchange levels within the spatial VPP model[47]. The VPPC makes decisions and provides some modifications of its requests to the VPP resources in real time by utilizing the measured data collected with the smart meters and the updated information from the energy market. The aggregated EV batteries under the VPP architecture can be used to balance the demand and consumption forecast deviations of the electric power grid.

3.4 Role of Energy Storage in Future Electricity networks

The transition to a low carbon electricity sector will create challenges for the electricity system. A decarbonised electricity system requires a radically different generation mix from that seen conventionally. It will include a considerable quantity of capacity that is less flexible than the present fleet, whether due to technical inflexibility (such as variable or intermittent renewable generation) or commercial inflexibility (due to low or zero marginal costs, perhaps exacerbated by output-based support mechanisms). To manage these challenges, it will, in future, need to draw on flexibility from a wide range of sources to balance the system and provide security of supply. Energy storage is one source of flexibility which could help to balance the system and provide an alternative to traditional network reinforcement.

The generation mix is evolving in response to policy goals to pursue decarbonisation of the power sector and to increase the proportion of electricity generated from renewable sources. The proportion

[45] Dashora Y, Barnes JW, Pillai RS, Combs T, Hilliard M. Optimized energy management for large organizations utilizing an on-site PHEV fleet, storage devices and renewable electricity generation. Energy Syst 2012;3:133–51.

[46] Sortomme E, El-Sharkawi MA. Optimal charging strategies for unidirectional vehicle-to-grid. IEEE Trans Smart Grid 2011;2(1):131–8.

[47] Raab AF, et al. Virtual power plant control concepts with electric vehicles. In: Procedings of the 16th International conference on intelligent systems application to power system (ISAP); 2011.

of generation provided by wind and solar capacity is increasing as a result and this trend is expected to continue going forward. Wind and solar generation are 'autonomous' in nature and have limited commercial sensitivity to the system needs (in response to market prices). As a result, greater flexibility will be needed to manage the unpredictability and variability of intermittent generation. Electricity storage is one possible source of flexibility. However, deployment of storage is limited at present, with large scale pumped storage hydro schemes the main source. In addition to developments in generation, the evolution of 'smart' technologies has the potential to change patterns of consumption and to open up new options for grid management. Electricity storage has a role to play here too, helping to manage potentially more variable patterns of usage and the implications for the grid. The Smarter Network Storage (SNS)[48] project is focused upon demonstrating the potential benefits of employing storage solution on a distribution network in place of conventional network reinforcement. The business case for this is linked to the economic value of the avoided network reinforcement costs and the ability for storage to capture revenue from providing ancillary services and/or bulk energy trading. This, in turn, is driven by the regulatory and market arrangements and their implications for storage deployment.

Energy storage will play a key role in enabling the EU to develop a low-carbon electricity system. Energy storage can supply more flexibility and balancing to the grid, providing a back-up to intermittent renewable energy. Locally, it can improve the management of distribution networks, reducing costs and improving efficiency. In this way, it can ease the market introduction of renewables, accelerate the decarbonisation of the electricity grid, improve the security and efficiency of electricity transmission and distribution (reduce unplanned loop flows, grid congestion, voltage and frequency variations), stabilise market prices for electricity, while also ensuring a higher security of energy supply[49].

The technical diversity on offer across the range of energy storage technologies means that, collectively, they can be deployed for a wide range of applications, with each technology suited to a different space within this range. Figure 9 shows the range of services to which energy storage can be applied. The nature of potential service provision spans a range of applications including as represented Figure 3-4:

- Uninterruptible power supply: the provision of services to end-users to provide security and quality of electricity supplies;
- Grid support: the provision of services to distribution and transmission network operators to deliver system stability, manage peak load, voltage/thermal contracting management and provide balancing services; and
- Energy management: bulk energy trading.

Figure 3-5 provides a mapping between different storage options and their suitability for providing uninterruptible power supply, grid support and energy management, based on underlying technical characteristics.

[48] Smater-Network-Stoarge-LCNF-Interim-reprot-Regularty-Legal-Framework
[49] 'DG ENER Working Paper: The future role and challenges of Energy Storage' DG Energy, January 2013. http://ec.europa.eu/energy/infrastructure/doc/energy-storage/2013/energy_storage.pdf

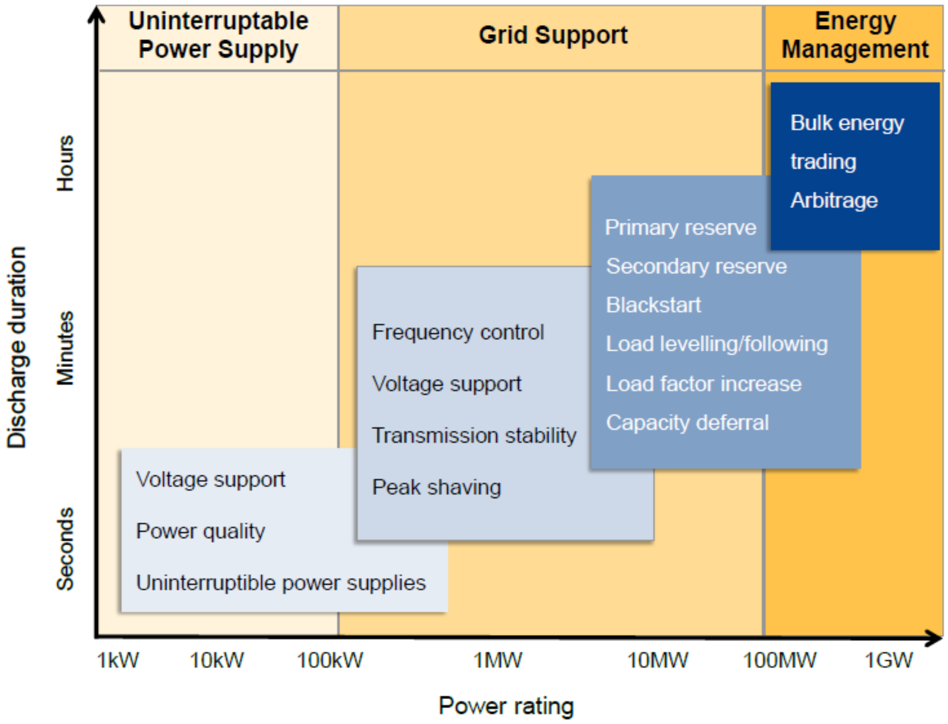

Figure 3-4 Range of Applications

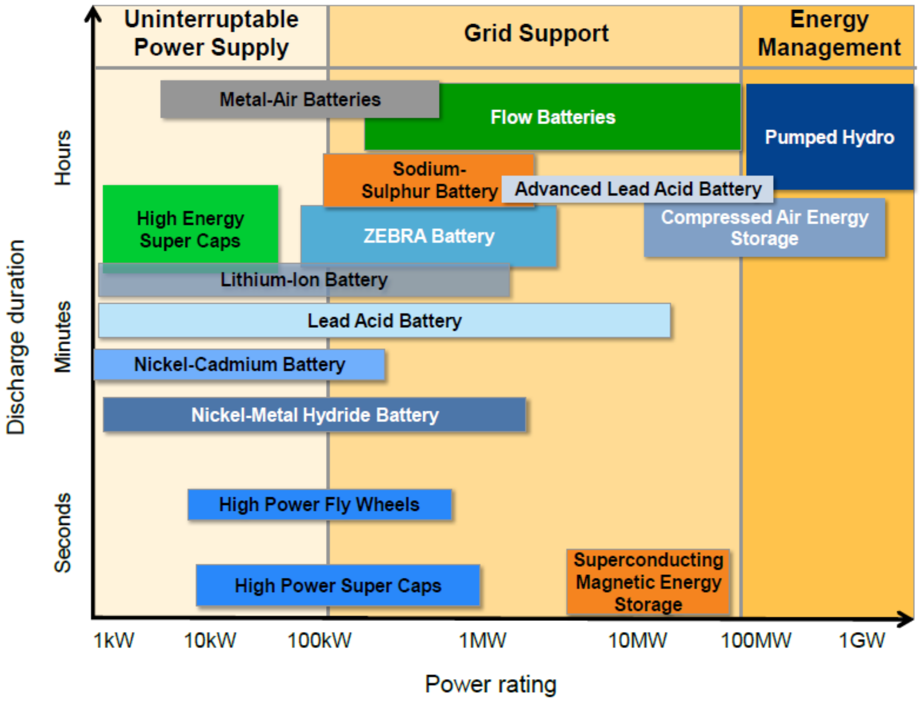

Figure 3-5 Mapping storage technologies to range of services

3.4.1 Value realisation of Energy storage

The characteristics of electricity storage means that it can be utilised for a variety of applications. Multiple uses means multiple sources of potential value, which creates a multi-layered business case. Making a business case work across these layers can be complex. Electricity storage has a broad span of potential applications across the sector. The range of applications and, therefore, sources of potential value are summarised in Figure 3-6. In addition, storage can provide wider benefits to the system such as the displacement of carbon emitting generation and/or high operating cost plants.

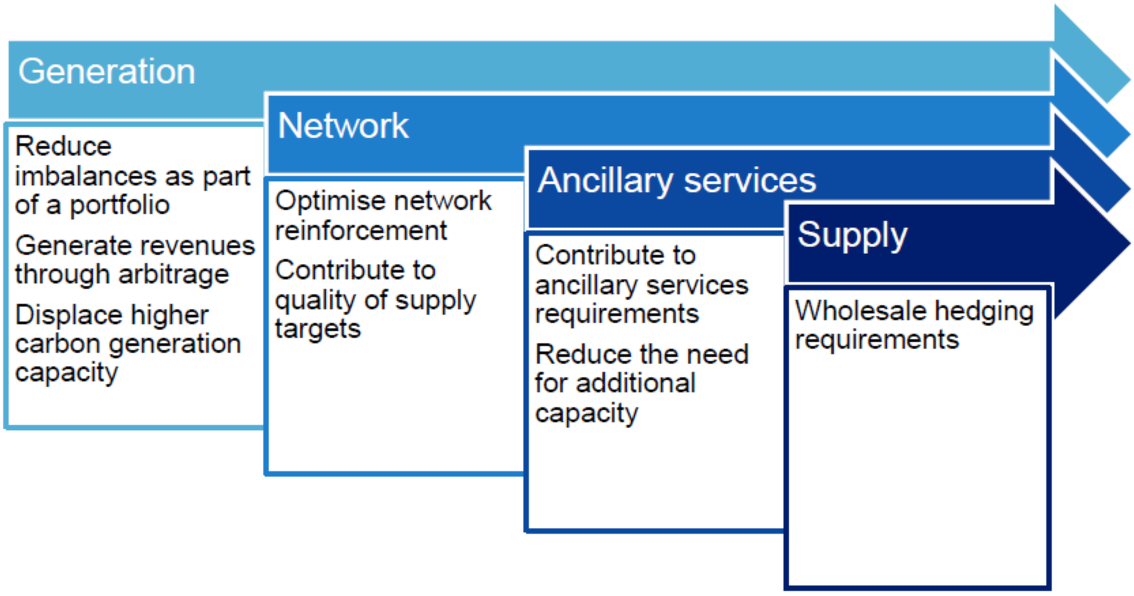

Figure 3-6 Range of possible applications across the value chain

Some value stems from market activities, such as participation within the wholesale market or provision of ancillary services to the transmission system operator. Other sources of value are linked to benefits from avoided network capex and displaced generation capacity. The stack of possible sources of value is illustrated in Figure 3-7.

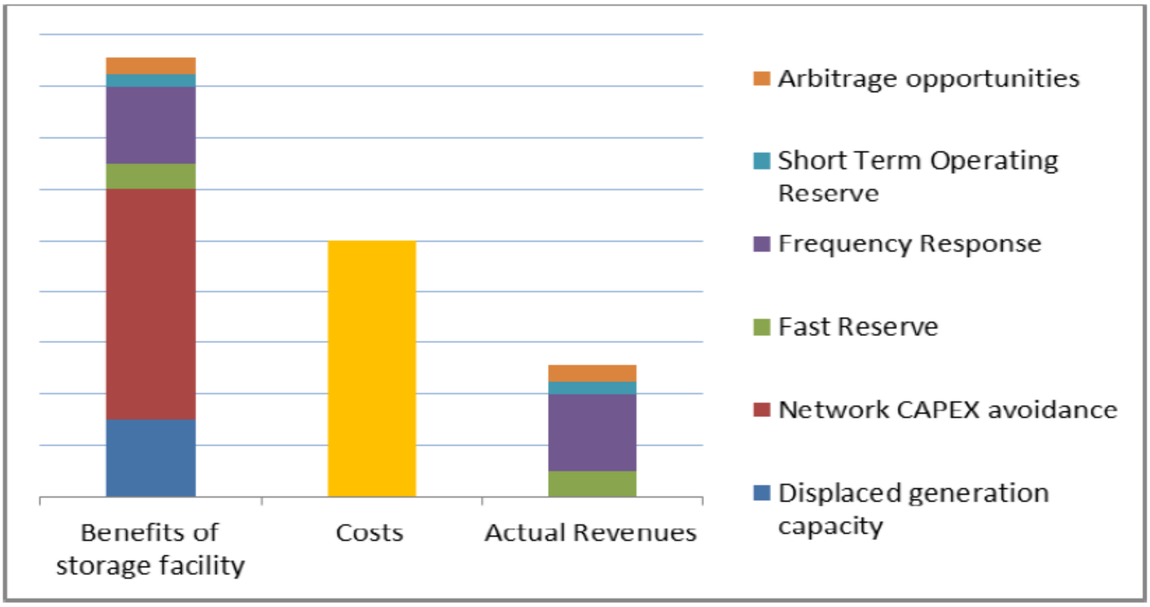

Figure 3-7 Costs and benefits of an example storage facility

3.5 Balancing Services

In electricity markets such as the GB market, generators dispatch their plant to meet their contracted electricity sales. However, it is ultimately the responsibility of National Grid to ensure that generation and demand are balanced at all times and in all locations. In order to fulfil this duty, National Grid employs a range of tools. These tools (collectively known as Balancing or Ancillary Services) can be broadly broken down as follows:

- **Frequency Response**: the automatic provision of increased generation or demand reduction in response to a drop in system frequency. This can be further subdivided into Primary and Secondary response:
- Primary response is defined as the sustained output from 10 seconds to 30 seconds following a loss of 0.8Hz.
- Secondary response is defined as the sustained output from 30 seconds to 30 minutes for a loss of 0.5Hz.
- **Reserve**: the manual provision of increased generation or demand reduction over a period of minutes or hours in response to an instruction from National Grid; and
- **System Security**: the provision of generation or demand variation (i.e. increase or reduction as appropriate in the specific circumstances) in order to ease local transmission constraints or other system security issues.

3.6 Forecasting & time scheduling

As the world's population is gradually increasing with more countries being introduced to urbanisation, this causes the demand of electricity to escalate. Therefore, implementation of load forecasting and demand side management has been proposed to tackle this problem. Having an accurate load forecasting algorithm allows electric utility grids to plan ahead and have a better understanding of future demands thus able to supply adequate power to their consumers. Demand side management also helps to reduce peak load demands and allow electric utilities to reshape consumer's load profile.

Depending on the kind of planning strategies being used, load forecast can be classified into four different categories. Since there is no single forecast that can solve all the problems of the electric utility grids, a common practice is to match different forecast for different purposes. According to different forecast horizons and resolutions, load forecasting problem is being classified into the following four categories[50]:

- Very Short-term load forecasting: few minutes to few hours ahead
- Short-term load forecasting: One day to two weeks ahead
- Medium-term load forecasting: Two weeks to one to three years ahead
- Long-term load forecasting: one or three to fifty years ahead

Majority of the research done in the market for load forecasting falls under the first three categories namely; Very Short-term, Short-term and Medium-term. Long-term load forecasting is mostly used by electric utilities for making decisions that involves investments. An example will be to decide if it is feasible to install a substation at a certain location. An accurate Long-term forecast gives electric utilities a better understanding of future demands allowing them to make viable decisions for further planning, maintenance and expansion. The deployment of smart grid technologies brings new opportunities as well as challenges to the field. On a smart grid, load data can be collected at a much higher geographical granularity and frequency than before, by means of thousands of smart meters.

A study form Smarter Network Storage (SNS) [51]energy shows that to establish if there is a need to allocate and energy from the ESS for the DNO peak-shaving service, a demand forecast of whole substation average power in each half-hour (HH) period in the forward schedule is required. To align with the time scales on which scheduling will take place, it must be possible the demand forecast from 1 to 8760 hours in advance. Separate forecast models should be considered for short-term (72-hour), medium-term (4-week) and Long-term (12-month) windows.

3.6.1 Approaches to demand forecasting

Two branches of approach to demand forecasting can be considered; time-series methods or end-use load modelling. Time-series methods are considerably more mature and the available data is appropriate for using this approach. Estimates of the success that could be achieved through an end-use load modelling approach are not well defined and as such it is not suitable for this import aspect of SNS[7]. These alternative approaches and subsequent variants are illustrated in Figure 3-8.

[50] Tao Hong and Mohammad Shahidehpour. Load Forecasting Case Study. National Association of Regulatory Commissioners, pages 1–171, 2015

51 Smarter Network Storage- Long Term Demand Forecasting, V1:24, April 2014.

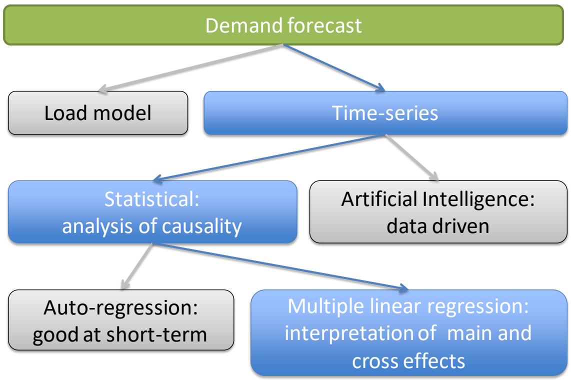

Figure 3-8 Demand forecasting solution hierarchy

Time-series based techniques fall into two broad categories; statistical methods or artificial intelligence techniques. Statistical methods fit parameters to an analytic expression that uses the endogenous past demand profile and possibly exogenous data, such as temperature and economic output[52]. A range of artificial intelligence techniques have been used in demand forecasting, including Artificial Neural Networks[53] which typically make use of plentiful historical data to uncover underlying patterns of variation and carry this forward in time, without seeking to identify the underlying causes of demand variation.

The literature suggests that artificial intelligence techniques do not generally offer significant improvements over more established statistical methods. Further, they can perform considerably less well and since they are based data rather than explanatory variables, it can be difficult to discern why a technique is or is not performing to a satisfactory standard.

Statistical models can again be divided into a number of alternatives including semi-parametric, auto-regressive or multiple linear regressive. Auto-regressive models use the endogenous historical demand data alone and can work well for short-term load forecasting. A multiple linear regression takes in any number of endogenous and exogenous data sources. Whichever method is used, over-fitting of data has to be avoided. An over-fitted model will perform very well within the data that was used to construct the model (in-sample), but out-of-sample performance is likely to be compromised by variations that were not seen in-sample. Over-fitting can be worse than under-fitting.

As mentioned earlier, demand forecasting horizons are typically split into three timescales, short, medium and long-term. Different techniques and variations within techniques have been applied at these alternative timescales as the requirements and explanatory variables can be different for each timescale. Within-day (typically hourly) meteorological forecast data has been shown to improve short-term and medium-term demand forecasts. Weather forecast data ceases to improve demand forecasting accuracy once a medium-term (31-day) timescale is reached[54]. The error in the weather forecast can be sufficiently large so as to create a worse error in the demand forecast than would have been present without any forecast weather data.

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52 Fan, S., 2012. Short-term load forecasting based on a semi-parametric additive model. IEEE Transactions on Power Systems, 27(1), p134-141.

53 Hippert, H.S., Pedreira, C.E. and Souza, R.C., 2001. Neural networks for short-term load forecasting: a review and evaluation. IEEE Transactions on Power Systems, 16(1), p44-55.

54 Chen, B., Chang, M. and Lin, C, 2004. Load forecasting using support vector machines: a study on EUNITE competition 2001. IEEE Transactions on Power Systems, 19(4), p1821-1830.

When considering the timescales on which demand forecasting can be improved, refinement of a demand forecast is only warranted if there is an improvement in the accuracy of an explanatory variable. It is possible to provide a confidence interval for upcoming demand, using a process called density forecasting[55]. A procedure called bootstrapping can be used to do this using the statistical characteristics of the explanatory variables in the forecasting model to give a resulting spread in the demand forecast.

A number of metrics are used to report demand forecast accuracy and it is not generally clear from reports of technical performance as to how far the worst case demand forecast deviates from the mean. Typical metrics are Mean Absolute Percentage Error (MAPE) or Mean Absolute Error (MAE). Based on reports in the literature for short-term demand forecasting a MAPE in the range 1-3% is likely to be achievable, however the Maximum Percentage Error must be worse than this. Longer-term forecasts are increasingly inaccurate.

In summary, the widely used forecasting tools developed can be classified into three typical approaches: physical model, statistics model and computational intelligent model. The numerical weather prediction (NWP) model is the basis of physical approach, where the variability of meteorological processes is described by atmospheric mesoscale model or global databases of meteor measurements. In terms of statistical methods, the forecasting value has a linear correlation with historical data in a specified time duration. The frequently used statistic methods consist of auto-regression (AR), moving average (MA), and auto-regression moving average (ARMA), auto-regression integrated moving average (ARIMA). Meanwhile, Box-Jenkins approach is an effective tool to identify the components and parameters in time series, while Kalman filter technique, also cited as a parametric model, is implemented based on historical data. Hence, the artificial intelligent approach neglects physical process from input variables and output performance and replaces it with a ‘black box’, which is composed of a single model or hybrid model. The widely used single models include fuzzy logic, artificial neural network (ANN), support vector regression (SVR), wavelet transform (WT), genetic algorithm (GA), expert systems. The hybrid system is to integrate one or more algorithms to pursue a higher forecasting accuracy. The most widely accepted hybrid model is the adaptive neural fuzzy inference system (ANFIS). The forecasting algorithms are summarized in Figure 3-9.

55 Hyndman, R.J., Fan, S., 2010. Density forecasting for long-term peak electricity demand. IEEE Transactions on Power Systems, 25(2), p1142-1153.

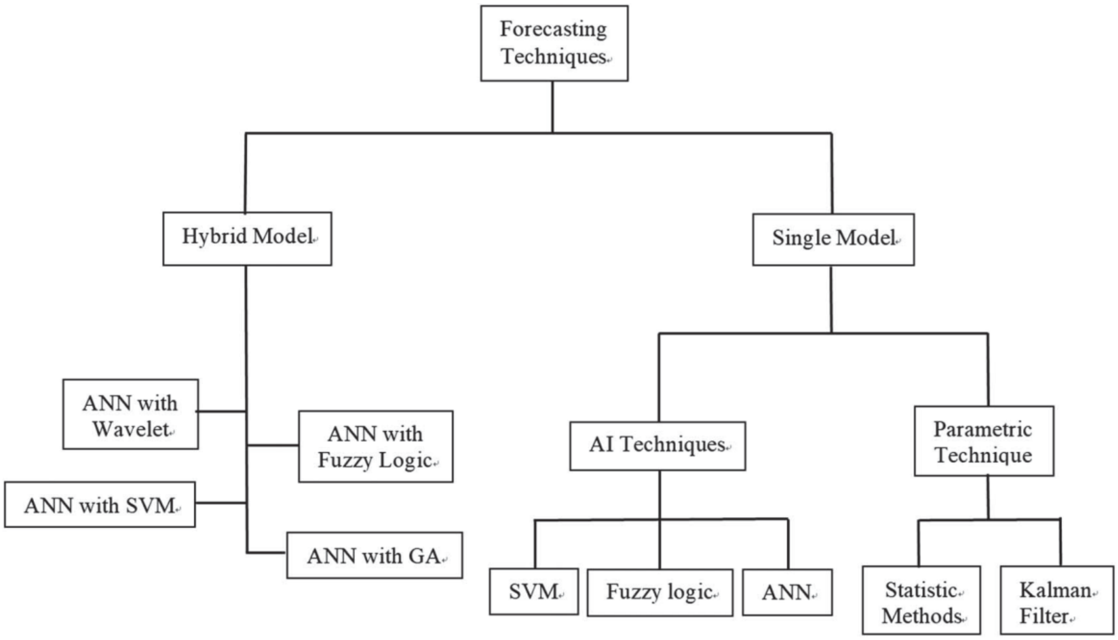

Figure 3-9 Overview of the forecasting techniques

Recently, *deep learning* has become one of the most active technologies in many research areas. As opposed to shallow learning, deep learning usually refers to stacking multiple layers of neural network and relying on stochastic optimisation to perform machine learning tasks. A varying number of layers can provide a different level of abstraction to improve the learning ability and task performance[56]. Especially, the long short-term memory (LSTM) recurrent neural network (RNN), which was originally introduced by Hochreiter et al.[57], has received enormous attention in the realm of sequence learning.

Forecasting demand is essential for the effective control and operation of energy storage; an effective demand forecast allows the storage facility to engage in commercial activities while ensuring the state of charge is sufficient should it be required to engage in peak shaving.

3.7 Strategies to mitigate power losses from a power distributor perspective

No system can be 100% efficient and electricity networks are no different. The losses on an electricity network are made up of fixed losses, variable load losses and also theft from the network. Making decisions which change network losses in isolation from other aspects of technical and economic performance is seldom achievable. The electricity system is complex and different parameters are interrelated within a given network and across network and operator boundaries. Losses on distribution networks are a major component of the overall losses in power system but because of this whole system interrelationship the management of losses should not just be limited to

[56] Y. Bengio, A. Courville, and P. Vincent, "Representation Learning: A Review and New Perspectives," *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 35, pp. 1798-1828, 2013.

[57] S. Hochreiter and J. Schmidhuber, "Long short-term memory," *Neural computation,* vol. 9, pp. 1735-1780, 1997.

consideration of its distribution network but should involve a system wide perspective, taking into account actors in the rest of the electricity network.

This is important because the transition to a low carbon economy involving the electrification of transport and heat has the potential to increase system losses as network equipment is more highly utilised. Any such increase needs to be weighed against the carbon reduction benefit arising from this transition. The move towards a distribution system operator role may offer market based and smarter solution based opportunities to manage losses, and will be facilitated by better losses visibility and more potential for losses control, for example maximizing the ability of zero-carbon generators to dispatch. Such solutions themselves may involve local increases in losses but again deliver a net carbon reduction benefit. Conversely a smarter flexible energy system with large amounts of distributed generation offers the prospect to actively manage power flow to minimise the need to move power over long distances. Whole system thinking will be important so that overall benefits maximised and costs minimised across the energy system[58]. Losses philosophy should be defined as a whole system approach that ensures network decisions are made using techno-economic analysis so that losses are appropriately valued to provide best aggregate benefit to customers in carbon reduction as well as economic terms.

Losses in electricity networks are a significant part of overall losses in the electric power system. A reduction of network losses would make an important contribution to the EU's plan to increase energy efficiency in electricity supply. An analysis of national practices have provided the following aspects of network losses[59]:

Definitions: There is no common definition of losses within the EU. This leads to a situation where different definitions in the Member States exist. It is obvious that technical losses are the main part of network losses but there are Member States where non-technical losses like theft or non-metered consumption are included in the losses. A comparison of network losses needs a common definition of losses.

Calculation methodologies: The definition of network losses is very complicated, because losses have to be calculated and cannot be measured in most cases. The measurement of network losses would only be possible in networks with continuous metering of all consumption and generation, which is not currently the case, especially in distribution networks. As network losses must be calculated, a comparison of network losses must also include an overview of the different calculation methodologies in the Member States. It is also of relevance at which voltage levels it is possible to measure network losses.

Consideration of costs in the tariff system: In many Member States, there are separate network tariff components for losses, whereas in some Member States losses are included in a common network tariff.

Regulatory incentives for the reduction of losses: Energy efficiency is an issue of increasing importance. Therefore, an incentive for taking measures to reduce losses should be provided to network operators. There are also different approaches for such incentives and these have to be compared.

3.7.1 Smart Meters

The roll-out of the smart meters will provide an opportunity for DSO to access network data at lower voltage levels of distribution networks than ever before. It should be noted that the benefits in this

[58] Northern Powergrid: Our business plan for 2015-2023, Strategy for losses, November 2017.
[59] Treatment of Losses by Network Operators, E08-ENM-04-03, ERGEG Position Paper for public consultation

area are dependent on the availability of both data for decision making and, in the DSR area, agreements on how decisions might be implemented. For this reason loss reductions are subject to:

- A swift and successful roll out of smart meters;
- Availability of consumption data at a sufficiently granular level and low customer aggregation;
- Methods of passing cost signals or device management signals to customers at a reasonable cost - this will depend on suppliers being minded to facilitate this.

It must be noted that to provide the increased functionality the new meters require more energy to operate. This increase although small at the individual property level has a significant aggregated effect. Despite the increased demand the new meters are expected to facilitate significant reductions in peak demand from implementation of time of use tariffs and hence reduce losses. Additionally, it is seen further scope to benefit from smart meters in multiple areas; from demand side response to supporting the identification of unmetered supplies.

3.7.2 Calculation of electrical losses

Fixed losses are calculated based on physical principles using manufacturers or standard loss data on a per asset basis for transformers or on a per km basis for cables and overhead lines verified over time using measurement on the system. This type of loss can therefore be robustly assessed either on an individual asset or total network basis without the need for onerous detailed calculation. Variable losses have a complex relationship to customer demand, the customer maximum demand, the customer load profile and the load profile of system load. Since all four of these vary with time of day and time of year, it is only possible to predict how losses will change with any one parameter by considering all four. Losses are calculated by calculating the overall efficiency of the network. This is by subtracting the energy leaving the system from the energy entering the system. The metering accuracy at the entry and exit points is critical in ensuring losses are accurate. As most exit points (domestic meters) have an accuracy which is similar to the proportion of losses experienced, it is therefore not possible to calculate losses to within an accuracy level of measurement or monitoring that could inform an efficiency initiative. Accurate measurement of real time electrical losses on the distribution system is not and may not be achievable for many years to come, and will depend on the eventual profile and final extent of the smart meter roll out programme and how pervasive measurement on various parts of the network becomes. Even when the smart metering roll out is complete the accuracy of smart meters is of the same order of magnitude as the proportion of the overall losses (i.e. 2% accurate meter readings used to calculate losses values which are around of 5% of the total energy consumed). Furthermore any data aggregation requirements will make losses calculations less robust. Current methods of calculating losses are based upon crude models that simply allocate the difference between energy purchased and distributed across the network assets in an educated way. Having long recognised that that movement in this loss figure is very insensitive to investment that DSO make but very sensitive to the data accuracy and the behaviour / efficiency of customers; it cannot be influenced significantly and demonstrably. It is a question how the future smart metering infrastructure[60] for domestic customers, covering 50% electrical demand, can be used to improve our understanding of network electrical losses.

[60] CIRED 2017: Analyzing the ability of Smart Meter Data to Provide Accurate Information to the UK DNOs (http://cired.net/publications/cired2017/pdfs/CIRED2017_0654_final.pdf)

3.7.3 EU target and directive

2020 targets

One of the five 2020 headline targets agreed across the EU relates to Climate Change and Energy. These are split into an overall reduction in greenhouse gas emissions of 20% from 1990 levels; 20% of energy from renewables; and 20% increase in energy efficiency. These targets have been translated into national targets by the EU which takes into account the different situations and circumstances of each member state.

Ecodesign and energy labelling policies

The Ecodesign Directive (2009/125/EC) establishes a framework to set ecological requirements for energy-using and energy-related products sold in all 27 EU Member States. The requirements to be introduced in three tiers: 2015; 2020 (and 2025 for larger pole mounted transformers) and include:

- Minimum energy performance requirements for medium power transformers
- Peak efficiency requirements for large power transformers, and
- Product information requirements.

The directive references the performance categories described in EN50464-1:2007. Figure 3-10 below shows how existing ground mounted distribution transformers compare against the expected minimum requirements for the Ecodesign directive.

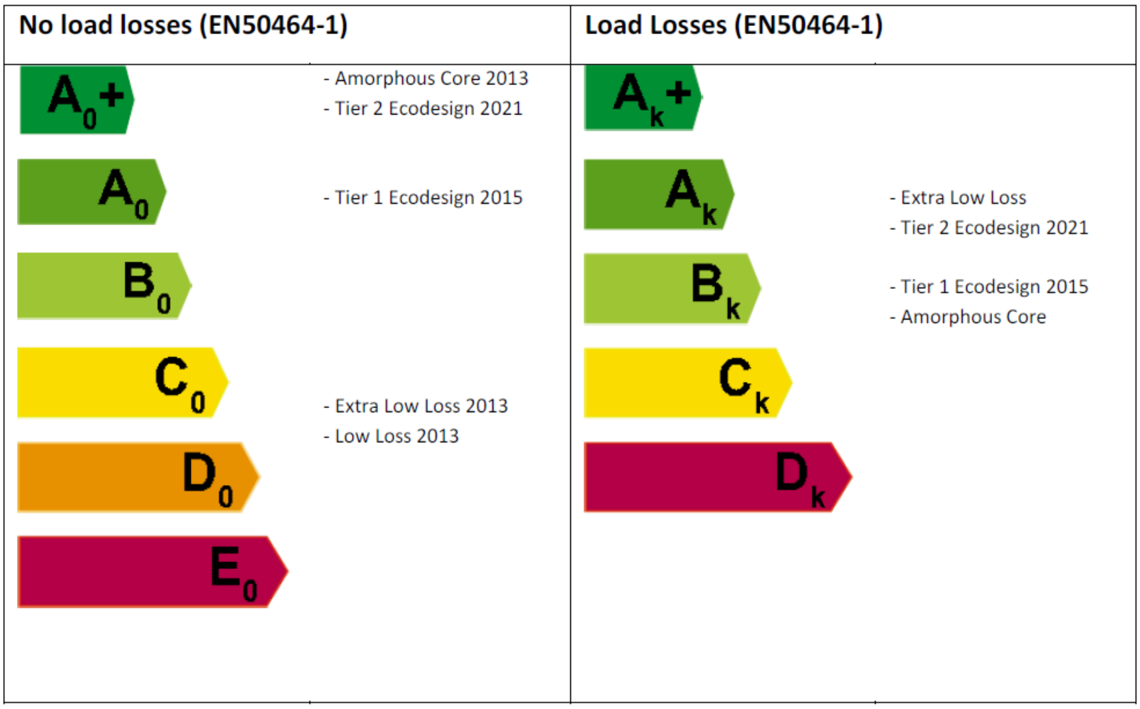

Figure 3-10 Existing ground distribution transformers

EU network codes

The European Network of Transmission System Operators for Electricity (ENTSO-E) represents 41 transmission system operators (TSOs) from 34 European countries. ENTSO-E's Network Code on

Demand Connection will help to facilitate cross-border network issues and market integration issues across the EU. The code helps to establish a secure interconnected transmission system through close co-operation between generators, transmission network operators and distribution network operators.

Article 16 of the code places a restriction on Reactive Power flows at the transmission-distribution interface. The existing reactive power range is not specified by the Grid Code. These limits have been implemented primarily from a stability perspective; however they will inevitably have a positive effect on system losses. Within this code it places an emphasis on the cost benefit analysis to justify the whole system savings. If reactive power equipment was installed at the interface with National Grid, the only cost savings would be on National Grid's transmission system but potentially paid for by DSO. However installing power factor correction on the lower voltage networks would have benefits for DSO, TSO and National Grid.

3.7.4 Overall distribution of Electrical losses

The national definition of what voltage levels are operated by TSO and DSO differs from country to country. If TSO operates not only the transmission grid but also the regional grids, the average percentage of losses will be higher than if the TSO operators only the transmission grid. If the DSO operators not only the distribution grids but also the regional grids, the average percentage of losses will be lower than if the DSO operates only the distribution grids. The DSO losses generally include theft, the higher the level of the theft, the higher the percentages of losses. In Europe, excluding the UK, nontechnical losses (NTL) include theft, non-registered consumption, own consumption, non-metered supplies such as public lighting and errors in metering, billing and data processing (including time lags between meter readings and statistical calculation). Total distribution losses[61] range from 2.3% (Sweden) to 11.8% (Poland), with Romania being an outlier at 13.5%. Around 19% of energy used in Turkey is illegal. In Spain 35% to 45% of NTL are estimated to be due to fraud. The regulator in the UK [OFGEM 2015] estimates that total T&D losses in the UK were 7.2% in 2013, of which most (about 73%) were technical losses on the distribution system. NTL on the distribution system were about 4% of the total losses (or 0.27% of energy supplied to the transmission system).

Figure 3-11 below gives an indication of how the total system losses are distributed across the network assets in a typical network in UK. It can be seen that over two thirds of the energy lost on the system is at HV and below. Figures on losses over the DNOs' networks in Great Britain are thought to be around 5-6% of total electricity generated[62]. This represents the largest component of the DNOs Carbon footprint, for example this represents 93% of Northern Powergrid's carbon footprint[63]. Broadly this translates to around 0.84 MTonnes of CO_2 emitted annually due to losses on the Northern Powergrid network. Reducing losses on distribution networks can have a significant effect on overall CO_2 emissions for the country. For example electrical losses on distribution networks are estimated to contribute approximately 1.5% of GB's overall greenhouse gas emissions[64], and although reducing losses to zero is not possible, any significant reduction in losses could make an important impact on the overall emissions of the UK as long as doing its not at the expense of greater savings elsewhere on the energy system.

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[61] Congrès International des Réseaux Electriques de Distribution International Conference on Electricity Distribution - Reduction of Technical and Non-Technical Losses in Distribution Networks - CIRED WG CC-2015-2;

[62] Ofgem (2010). Factsheet "Electricity Distribution Units and Loss Percentages Summary"

[63] NPg (2016-2017). Environment Report" http://www.northernpowergrid.com/asset/0/document/2724.pdf

[64] http://www.ofgem.gov.uk/Networks/ElecDist/Policy/losses-incentive-mechanism/Pages/index.aspx

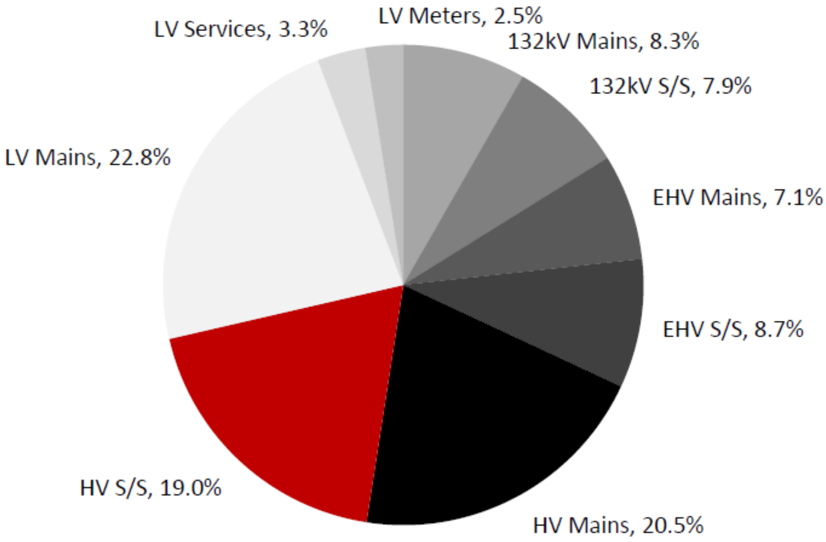

Figure 3-11 Typical overall distribution of percentage losses in UK (adding up to 100%)

EHV (400kV); HV (275kV); LV (11kV, 20kV, 33kV, 66kV)

3.7.5 Recommendation to reduce losses

The loss reduction strategy has highlighted a multi-layered approach to reducing losses. Several of the existing loss reduction are straight forward to implement and are incorporated into everyday asset replacement and reinforcement schemes. Clearly the EU Ecodesign Directive will have the greatest impact and DSO will continue work to understand the wider implications of this legislation. The work will be continued with manufacturers to ensure better cost certainty and technical differences to existing stock are understood prior to mass adoption.

Losses in the distribution of electricity cannot be eliminated, but can be minimized by proper planning of the distribution systems to ensure that power remains within limits. Some of the ways to reduce losses include[65]:

- The use of proper jointing techniques, and keeping the number of the joints to a minimum.
- Regular inspection of the connections, isolators, drop out fuses, LT switches, transformers, transformer bushing-stem, and other distribution equipment.
- Proper selection of conductor size, as well as the transformer in terms of efficiency, size and location (taking into account MV transformers are designed considering contingencies situations). In particular, it is important to locate the distribution transformers at the load enter and if possible keep the number to a minimum.
- Feeding heavy consumers directly from the feeders.
- Maintaining the network components and replacing those that are deteriorating, worn out or faulty.
- Proper load management and load balancing.
- The use of electronic meters which are accurate and tamper-proof.

[65] http://electrical-engineering-portal.com/total-losses-in-power-distribution-and-transmission-lines-1

- Improving power factor by adding shunt capacitors.

Options for further loss reduction

A summary of the different strategies and actions in terms of ease of deployment is shown in the following[66]:

Expand existing loss reduction techniques

It is important to note that due to the incremental nature of the asset replacement programmes and network reinforcement, any improvement in losses at lower voltage levels on the network can also have benefits on losses further upstream at higher voltages.

1) Increasing Cables sizing/ plant sizing (straight forward but costly)
2) Transformer loss specification (straight forward)
3) Increasing transformer sizing (straight forward)
4) Network configuration at planning stage (straight forward)
5) Power factor correction (moderate)
6) Power Quality (moderate)
7) Load imbalance (moderate)
8) Loss measurement (Difficult)
9) (Theft Reduction)

New Technologies

10) Superconductors (difficult and costly)
11) Low Loss transformers (Moderate)
12) Design of the energy efficient substation to be carbon neutral (Moderate)

Changes to network operations

13) Voltage reduction at night (moderate)
14) Switching out under-utilised plant (moderate)

3.8 Factors and initiatives affecting Metro Energy Efficiency and CO_2 emissions

Some of the actions and factors which can improve the energy efficiency of metros are summarised in Figure 3-12. This collection of factors is not comprehensive but it demonstrates that energy efficiency can be improved in a multitude of ways. Some initiatives may yield only small savings, but the sum of these may add up, over time, to a significant reduction in energy consumption. The greatest savings may lie in having regenerative braking and Automatic Train Operation (ATP) and Regulation systems which ensure that trains can run with minimum energy consumption using coasting. Ensuring that trains can run unimpeded and with minimal service perturbations and delay will reduce energy consumption from avoidable acceleration. Managing the off-peak service provision is very important in optimising energy consumption; different ATO settings should be programmed for different times of the day (with maximum service capacity, frequency and speeds for the peak period only). However, ensuring the right level of service in the off-peak, balancing demand, service quality and operating costs (including energy consumption) should not be wholly driven by operating costs – metros should beware of the unintended consequences in losing passenger demand at the expense of reducing energy consumption.

[66] Northern Powergrid: Our business plan for 2015-2023, Strategy for losses, November 2017.

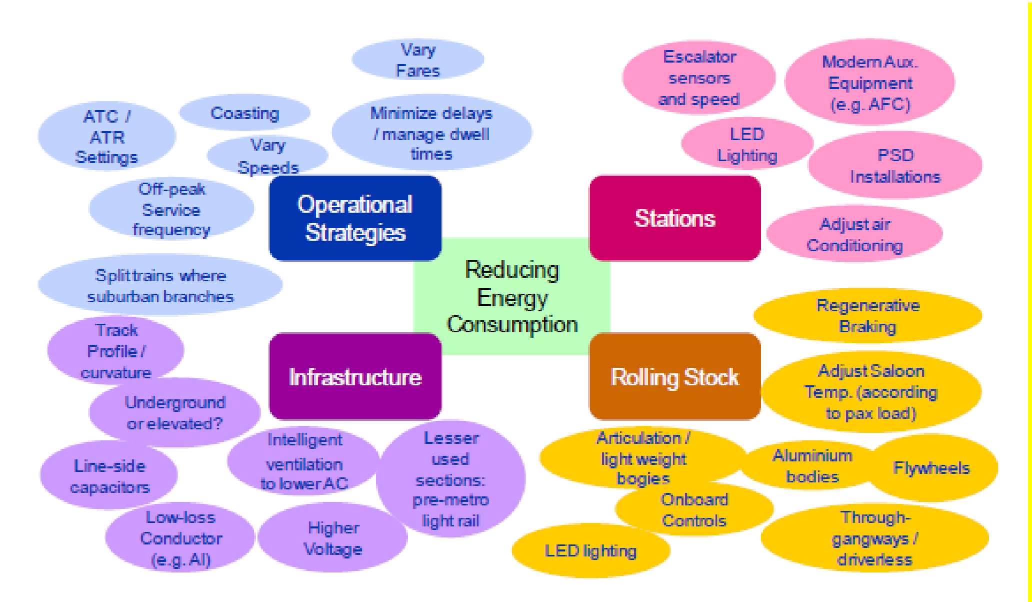

Figure 3-12 Initiatives to increase the energy efficiency of metros[67]

[67] R. Anderson, R. Maxwell, N.G. Harris, Maximizing the potential for metros to reduce energy consumption and deliver low-carbon transportation in cities, CoMET and Nova Groups/ Imperial College London, In: MetroRail Asia, Delhi, India; 2009

4 Interaction between the two networks

4.1 Factors mutually influencing losses

For railway network, the factors influencing powers losses include the train driving styles, operation timetables, train hotel load demand, feeding infrastructure arrangement, energy management strategy and non-traction power demand.

For distribution network, the technical losses mainly include the variable losses (load rated, e.g. transmission losses) and fixed losses (not related to load, e.g. corona losses, leakage current losses, iron losses). The factors influencing losses include conductor resistance, network imbalance, power factor, power quality, feed-in control, energy management, and transformer replacement.

If two networks are interconnected, additional power electronic and energy storage devices are employed. The railway network is not only a load requiring traction power from the distribution network, but also a generator to supply weak distribution network. One of main factors influencing losses is the effective usage of regenerative braking energy, which are mainly determined by train operation, feeding arrangement and power electronic controls. Other mutual factors influencing losses include the transmission cables, converters, transformers, energy storage efficiency, and power management.

4.2 Possible synergies for power loss minimisation

4.2.1 Train operation

Railway network is load and generator for distribution network. Optimising the train driving styles and timetable operations can reduce the peak power demand and increase the usage of regenerative braking energy. In the meanwhile, with a stable and optimal train operation, the availability of the regenerative braking power for distribution network is understood. Thus, the power losses can be reduced.

Optimising train operation can reduce the power demand from traction substation or understand the power demand schedule. When the traction substation requires low power from trains, it can be used to support the distribution network by the interconnection point.

4.2.2 Feeding arrangement and location

There are various feeding configurations can be used to inter-connect the railway network and distribution network. Different feeding configurations can be used for different purposes. Several configurations have been illustrated in Deliverable 2.1. One of the simplest connection is shown in Figure 4-1, where three power converters are used to connect the DC railway network, energy storage and distribution network. For this connection scheme, the following modes of operations are possible:

- Railway traction network supports the local grid during periods of large loads and no trains;
- Battery supports the local grid during periods of large loads but the railway is in use;
- Railway traction network recharges the battery when there is no significant load on the local grid and no trains or when a train is braking;
- The local grid recharges the battery when there is no significant load or there is availability of energy generation from renewable energy sources.

The feeding arrangement should be designed with the consideration of power transfer efficiency. The location of the inter-connection point, the length of cables, the convert and transformer efficiency and the effective usage of train regenerative braking energy or renewable power sources are the extra power losses due to the integration. These factors need to be considered in designing the feeding arrangement to reduce system losses.

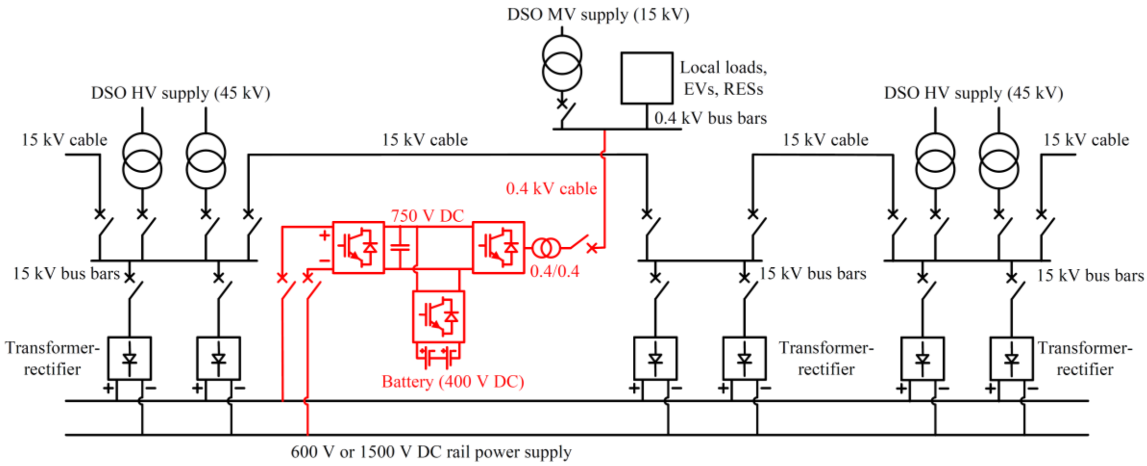

Figure 4-1. Connection of the sSOP to balance railway and local grids.

4.2.3 Inter-exchange converters

Transformer and rectifier losses are conventional fixed power losses for railway and power distribution networks. With the interconnection of railway and distribution networks, additional converters have to be employed, which lead to power losses. Conversion losses occur in power conditioning units and the total losses of converters are related to the semiconductor switching and conduction losses and losses in magnetic components. These losses are mainly dependent on converter switching frequency and current and junction temperature of semiconductors. The design of converters capacity and control is needed to be considered in the system energy optimisation.

4.2.4 Power management and controls

For the integrated networks, the loads and generators are from multiple directions (railway network, distribution network, energy storage and renewable energy sources). The power management and controls are essential in coordinating the power flows and reducing the power losses. To achieve the optimal power management, the load and generation power from each network is required and monitored. For railway, the power demand and regeneration are determined by train operation. For distribution network and electric vehicles, the load and output power can be analysed based on the customer data. For renewable energy sources, the generation power is based on the time and weather. The power management and control strategies can be optimised to minimise the power losses based on the network power flow data.

4.2.5 Auxiliary devices

With the increasing monitoring, metering and control devices for the integrated networks, the power demand and losses from the auxiliary devices are more than the conventional networks. Therefore, an evaluation of the power demand and losses of the auxiliary devices should be considered.

4.3 Management of the inter-exchange between the two networks

Using automated metering systems to collect energy consumption data in vehicles and other urban rail subsystems is not an energy efficiency action by itself, but it is indeed a valuable tool for optimising energy usage within the system. In fact, a good understanding of energy flows is paramount to identify areas with greater energy saving potential and to monitor the effects of the implemented measures. Furthermore, the information provided by energy meters is essential for energy billing purposes, an issue with growing relevance in liberalised railway markets[68]. Allowing private operators to pay for real energy consumption, rather than using average estimations, may represent a major incentive for them to apply energy efficiency measures[69]. In this regard, the standardisation of metering equipment and procedures is a key matter to be addressed.

4.3.1 Micro-generation of renewable power within the system

Depending on the characteristics of the system and on the availability of renewable energy sources in the area, the local generation of electricity may be an interesting solution to reduce power consumption from the public network. Thus, photovoltaic solar panels may be installed in stations and depots to partially meet their own demands. Similarly, solar panels could be installed along the track helping to feed the signalling systems and the substations auxiliaries. Furthermore, the use of solar panels on the rail vehicles' roof could provide enough power to supply their auxiliary systems[70], but the introduction of such additional weight is regarded as a serious concern. This hurdle might be overcome yet by utilising flexible, light panels based on polymer solar cells. Interestingly, using wind turbines in depots, stations or along the track could be an alternative (or a complement) to solar power systems[71]. Regardless of the kind of energy source, optimal integration of renewable power generation in railway systems will typically require the use of ESSs alongside dedicated power management controls, which may compromise the economic viability of these measures.

4.3.2 Energy storage systems for urban rail

The fast and outstanding development of both energy storage technologies and power electronics converters has enabled ESSs to become an excellent alternative for reusing the regenerated braking

[68] A. Gatti, A. Ghelardini, The European Energy Measurement System on board trains, In 9th World Congress on Railway Research – WCRR 2011, Lille, France; 2011.
69 CENELEC, EN 50463 – Railway applications: Energy measurement on board trains, 2007.
[70] P. Vorobiev, Y. Vorobiev, About the possibilities of using the renewable energy power sources on railway transport, J. Adv. Transport. doi: 10.1002/atr.189 (2011).
[71] TramStore21, Building sustainable and efficient tram depots for cities in the 21st century, TramStore21 project, 2013,
<http://www.tramstore21.eu/sites/default/files/brochures/Tramstore_Publication_ENG_DVD_v2.pdf>

energy within its own urban rail system[72]-[73]. ESSs can be installed either on board vehicles or at the track side. On-board ESSs permit trains to temporarily store their own braking energy and reutilise it in the next acceleration stages. On the other hand, stationary ESSs absorb the braking energy of any train in the system and deliver it when required for other vehicles' acceleration. Below, ESSs systems will be generally described and both on-board and stationary applications will be discussed.

Installation of on-board ESSs, the following advantages can be expected:

- Shaving of power peaks demanded during acceleration of vehicles, which leads to reduced energy costs and minimum resistive losses in the supply line.
- Limitation of voltage drops in the system network, which might eventually allow for a higher traffic density without further modification in the existing infrastructure.
- Certain power autonomy, for instance in emergency situations, in depot operations or in free-catenary applications such as lines going through historical city centres with visual impact restrictions.

In comparison with wayside storage solutions, on-board ESSs have the advantage of operating with higher efficiency due to the absence of line losses. Besides, the management of the recovered energy is simpler since the control is independent of traffic conditions. In contrast, on-board ESSs typically require a large space on the vehicle and introduce a significant increase of weight. Some studies have assessed that the additional mass due to on-board ESSs increases the traction energy consumption by 1% to 2%[74]. Owing to these hurdles, the installation of on-board ESSs is not commonly considered when retrofitting existing rolling stuck but when designing new vehicles.

Stationary ESSs essentially work absorbing the regenerated braking energy that cannot be used simultaneously in the system. The charge and discharge processes require an electronic controller that generally operates as a function of the voltage on line: when an overvoltage takes place as a result of any braking process, ESSs operate in "charging" mode absorbing the excess of regenerated energy on the line; in turn, when a voltage drop is detected, ESSs deliver the stored energy in order to keep the threshold value on the network. Wayside ESSs are usually installed in existing substations or in specific places where the contact line voltage variations are more significant, for instance near to stations. Stationary ESSs can be used to reduce the energy demand of the whole system, but also to stabilise the network voltage at weak points of the network, which is a major advantage over reversible substations. In fact, wayside ESSs might eliminate the need of additional feeding substations to compensate the voltage drops typically associated with end of lines. Similarly to on-board ESSs, stationary devices can greatly contribute to shave peaks of energy consumption during acceleration of vehicles, which in many cases imply considerable cost savings for operators. Besides, they might enable trains to reach the nearest station in-case of failure of the power supply, increasing the system security. When compared with on-board devices, wayside systems present the advantage of having fewer restrictions in terms of weight and required space. Moreover, stationary systems can recover energy from several braking vehicles at the same time and their implementation and maintenance do not affect operations. On the contrary, stationary systems are generally less efficient due to transmission losses taking place in the network. In summary, both on-board and wayside EEEs may lead to considerable traction energy savings in urban rail (typically between 15% and 30%); moreover, they may contribute to stabilise the network voltage and to shave the power consumption peaks.

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[72] M.A. Rosen, Energy Storage, Nova Science Publishers, Hauppauge, 2012.

[73] D. Iannuzzi, P. Tricoli, Speed-based state-of-charge tracking control for metro trains with on-board supercapacitors, IEEE T. Power Electr. 27 (2012) 2129–2140.

[74] M. Domínguez, A.P. Cucala, A. Fernández, R.R. Pecharromán, J. Blanquer, Energy efficiency on train control – design of metro ATO driving and impact of energy accumulation devices, In: 9th World Congress on Railway Research – WCRR 2011 (2011), Lille (France).

4.3.3 Smart energy measurement

This approach enables efficient management of all the energy sources in the network according to actual demand. This means, for instance, that the power from renewable sources, from regenerative braking or from the public grid can be either used to instantly meet the power demand of the system, or stored for later shaving peak consumptions, which may account for important cost savings. Applying the smart grid concept requires the development of an automatic control of voltage distribution within the network[75].

Furthermore, the integration of urban rail networks with other energy independent systems in their vicinity such as buildings, other urban mobility systems or renewable power generation plants, has been proposed as an extension of the smart grid concept for a “smart city” energy management. For instance, the excess regenerative braking energy from metro systems could help to power an urban network of electric vehicles[76]. Likewise, the heat from large underground systems could be used for heating purposes in buildings close to stations or to ventilation shafts[77]. Additionally, the power generated in nearby renewable energy plants could be used to feed the urban rail system itself, consequently reducing its environmental impact and improving its social image.

[75] Wang P, Yi J, Zangiabadi M, Lyons P, Taylor P. Evaluation of Voltage Control Approaches for Future Smart Distribution Networks. Energies 2017, 10(8), 1138.
[76] M. Falvo, R. Lamedica, R. Bartoni, G. Maranzano, Energy management in metro-transit systems: An innovative proposal toward an integrated and sustainable urban mobility system including plug-in electric vehicles, Electr. Pow. Syst. Res. 81 (2011) 2127-2138.
[77] A. le Clech, Heat extraction in underground railway tunnels, Eurotransport 3 (2005) 35–40.

5 Conclusion

This report has identified the degrees of freedom for railway network. The influence of train timetable, driving styles and train hotel loads on power losses and voltage profile has been analysed. The energy consumption of railway network is divided into traction energy (accounts for 60-70% of the total energy consumption) and the non-traction energy. Strategies to mitigate traction power losses including optimising train driving styles and operation timetables, designing route infrastructure, designing new train architectures and materials, reducing train auxiliary power, employing new traction power devices to increase regenerative braking energy usage, and smart energy management. Non-traction energy is consumed by stations, depots, buildings and technical railway operation (lighting, signalling, telecom, traffic control). The most significant energy savings can be found by introducing computerized heating control, replace life-expired track circuits with axle counters, improving PC power management, and upgrading lighting to more efficient types with matched control gear.

This report has also identified the degrees of freedom for distribution network losses reduction. The power quality, voltage and frequency level, smart grid management, balance services and forecasting and supply scheduling for distribution network have been addressed. The losses on an electricity network are made up of fixed losses, variable load losses and theft from the network. The loss reduction strategy has highlighted a multi-layered approach to reducing losses.

Finally, this report addressed the interaction between the railway and distribution networks. The mutual factors influencing the effective usage of regenerative braking energy, the transmission cables, converters, transformers, energy storage efficiency, and power management. The possible methods to reduce the power losses of the integrated system including

- Train operation (driving styles and timetables)
- Feeding arrangement and locations
- Inter-exchange converters
- Power management and controls
- Auxiliary devices management