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REETS: Realistic Energy Efficient Tunnel Solutions

Assessment of technologies with potential for energy reduction

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REETS
Realistic Energy Efficient Tunnel Solutions

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Author(s) of this deliverable (in alphabetical order):
Isabela Mocanu, AIT, Austria
James Peeling, TRL, United Kingdom
John Potter, Mouchel, United Kingdom
John Rands, DfL, United Kingdom
Matthew Wayman, TRL, United Kingdom

PEB Project Manager: Harald Buvik, Statens Vegvesen, Norway

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Executive summary

In terms of both construction and operation, tunnels are the most energy demanding of road infrastructure assets. The construction of a road tunnel is energy intensive due to the volume of excavation required and the energy embodied in the materials that form the structure of the tunnel. In operating a tunnel, energy is consumed to provide adequate lighting and ventilation for drivers, and to maintain drainage systems. A good deal of equipment is also installed to deal with emergency situations. With a tunnel's operational lifetime typically in excess of 100 years, energy usage through operation can soon outweigh that due to construction and, therefore, the former provided the focus for this project. The Realistic Energy Efficient Tunnel Solutions (REETS) project aims to enhance the energy efficiency of road tunnel operation, through the assessment, promotion and implementation of appropriate technologies.

REETS commenced with a wide-ranging review of energy-efficient technologies, considering those designed for tunnels, which could perhaps benefit from wider adoption, and those designed for other applications that have proved effective, and could be transferred for use in tunnels. Five technologies, identified as having potential to increase energy efficiency in road tunnels, have been assessed in terms of their practicality: reducing tunnel threshold luminance; LED lighting with 'closed loop' feedback; integrated tunnel monitoring systems; high voltage distribution and incentivising energy efficiency in tunnels.

A baseline picture of energy consumption was compiled as a first step towards evaluating the five technologies. Operational energy consumption was determined in the context of the other main contributors to life cycle energy consumption: construction and maintenance, and vehicle fuel consumption. Operational energy consumption was determined to have the second highest energy demand of the three facets: vehicle use was, predictably, the highest. Two types of tunnel were considered: a 5 km long single bore tunnel constructed using drill and blast; and a 2 km long twin-tube immersed concrete tunnel.

Qualitative assessments were undertaken of user safety and comfort. This showed that the five technologies would have a neutral to fair effect on user safety and comfort levels: it is paramount that these levels are at least maintained, if not enhanced, by the implementation of any new technology.

Energy efficiency was evaluated using carbon footprint as a proxy indicator. The quantitative assessment demonstrated life cycle energy savings for all five technologies, even after deductions had been made for capital carbon 'outlay' embodied in the technologies and their periodic replacement. The picture for life cycle cost was similar with the exception of one technology; integrated tunnel monitoring would require very significant outlay and frequent replacement. This was the only 'multi-functional' technology, in the sense that monitoring energy use was just one of its many applications; further tangible benefits will be realised from its other applications (many of which are safety-motivated) and these could offset the capital outlay. As a general rule of thumb, technologies aimed at improving the efficiency of energy supply to the tunnel realised the greatest benefits. Technologies aimed at smaller portions of overall energy use should not necessarily be discarded since they can deliver good returns with smaller capital outlays and have shorter payback periods.

1 Introduction

The Realistic Energy Efficient Tunnel Solution (REETS) project is being conducted in response to the 2013 call of the Programme of the Conference of European Directors of Roads (CEDR), a body formed by European National Road Administrations (NRAs). REETS seeks to provide solutions to assist NRAs seeking to reduce the use of energy associated with tunnel operations in an environment where public finances are increasingly stretched and energy prices are increasing.

A number of energy-reducing technologies for tunnels have already been investigated in the first deliverable of the project (Deliverable 1.1) and more are becoming available as technology advances. However, current regulations, standards and practices for tunnel operations have been devised to meet requirements for the safety and comfort of road users. Where technology enables improvements in energy efficiency to be realised, it is essential that current safety standards are not compromised as a result.

The project set out to meet the following objectives:

i. Identify energy-reducing technologies, or combinations of technologies, that will provide the greatest gains in energy efficiency, considering tunnels on a whole life basis;
ii. Assess the feasibility of these technologies, considering cost and carbon emissions associated with their installation and operation, as well as the effect on user safety and comfort;
iii. Conduct case studies to evaluate the costs and benefits that would result from the implementation of the technologies;
iv. Carry out the groundwork that NRAs can use to develop a business case for trialling the more promising options.

This deliverable presents the results of the second work package of REETS in which five technologies, identified as having potential to increase energy efficiency in road tunnels, are assessed in terms of their practicability. Cost and carbon emissions, associated with their installation and operation, have been quantified, while their impact on user safety and comfort has been assessed qualitatively.

Chapter Two presents an analysis of the characteristics of road tunnels across Europe. Chapter Three presents a description of the five technologies identified and a discussion on their potential for reducing energy consumption. The qualitative and quantitative assessment methodologies are presented and detailed, as well as the input data necessary to investigate their practicability. Chapter Four summarises the results and conclusions of the assessment, and the next steps for the project.

A summary of the profiles of the investigated technologies is presented in Annex A.

The five solutions that will be taken forward to the next stage of assessment are:

- Reducing tunnel threshold luminance
- LED lighting with ‘closed loop’ feedback
- Integrated tunnel monitoring systems
- High voltage distribution incorporating voltage optimisation, dynamic uninterruptible power supply (UPS) and avoiding dynamic oscillation
- Incentivising energy efficiency

2 Road tunnels in Europe

2.1 Types

The trans-European transport network (TEN-T) comprises the key transport arteries and hubs that are identified by the European Commission (EC) as being strategically important to the economic wellbeing of the European Community. The network, therefore, receives priority funding for upgrading and maintenance activities. The network covers all major modes of transport – road, rail, air and sea – throughout the EU-28 and to neighbouring countries e.g. Norway and Switzerland. The extent of the core road network is shown in Figure 2-1.

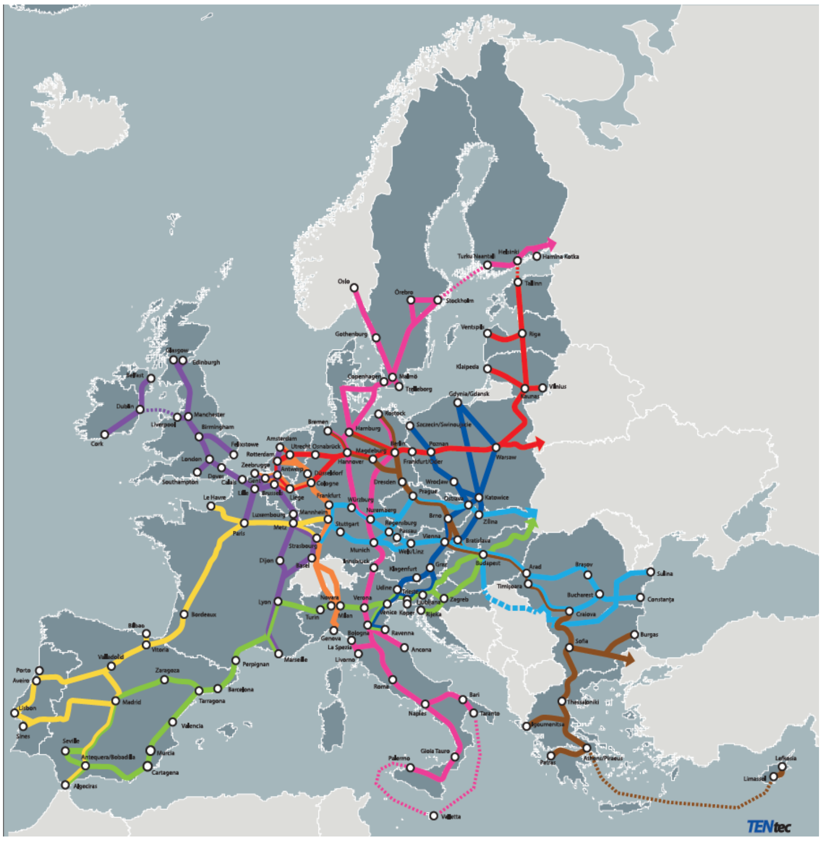


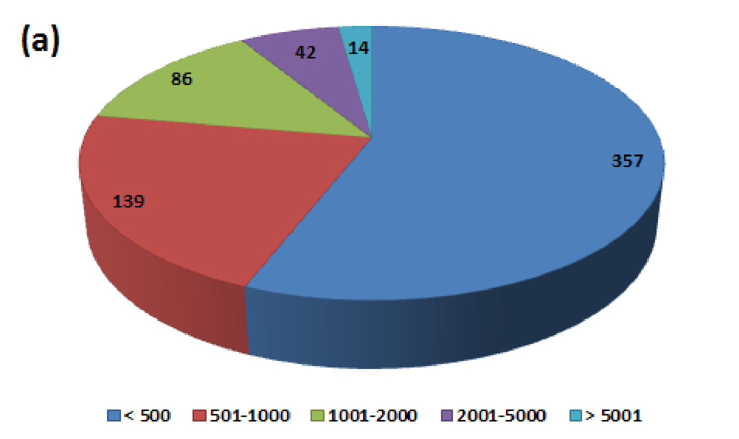
Figure 2-1: The TEN-T strategic road corridors [1]

An FP7 funded project entitled Security of Road Transport Networks (SeRoN) [2] reported on the bridge and tunnel assets on the TEN-T network. The project utilised surveys to capture details of those assets: the responses received were deemed 'reasonably representative' of the European road network. Around 26,400 km of the TEN-T road network was covered by the survey responses. The core TEN-T network covers 34,401 km and the comprehensive 136,706 km. The classification of the tunnels used in the SeRoN project is presented in Figure 2-2.

Types of Tunnels													
System													
Type		NATM Tunnel		TBM (bored)Tunnel		Immersed Tunnel		Cut and Cover Tunnel			Partly Covered Tunnel / Gallery		
Section		1 tube	2 tubes	1 tube	2 tubes	2 cells	3 cells	1 cell	2 cells	3 cells	1 cell	2 cells	3 cells
Type No.		1	2	3	4	5	6	7	8	9	10	11	12
Length [m]	< 500												
	500-1000												
	1000-2000												
	2000-5000												
	> 5000												

Figure 2-2: Tunnel classification used in the SeRoN project [2]

The data collected through the survey is presented in Figure 2-3.



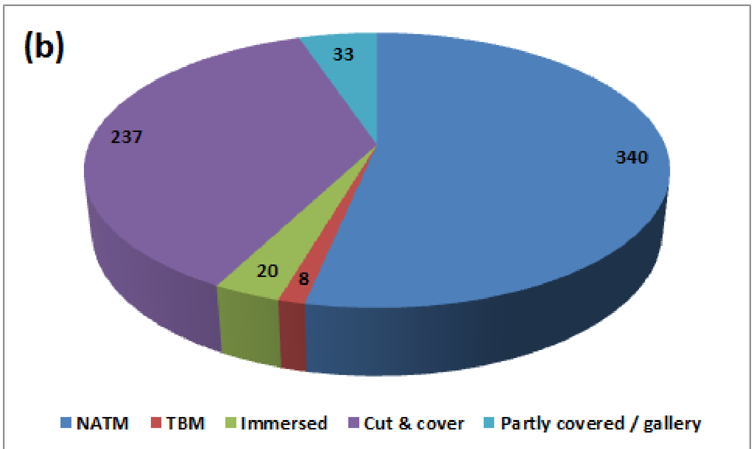


Figure 2-3: (a) Tunnel lengths and (b) type of tunnel on the TEN-T network (SeRoN data) [2]

Figure 2-3 indicates that just over half the tunnels are less than 500 m long. The predominant tunnel ‘type’ (53 %) [of construction] was the New Austrian Tunnelling Method (NATM), and the second most common type was ‘cut & cover’, representing 37 % of tunnels (these were probably the majority of the sub-500 m long tunnels). Further data on tunnels in Austria, Norway and the Netherlands was collected from tunnel operators and classified according to the method used in SeRoN. This information was provided by ASFINAG, Statens Vegvesen and Rijkswaterstaat respectively, as shown in Table 2-1 [3,4,5].

Table 2-1**:** Sources of tunnel energy consumption data

Country	**Data**	**Number of tunnels**
Austria (ASFiNAG)	Tunnel length and energy per year (in kWh) for 2012, 2013 and 2014	60
Norway (Statens Vegvesen)	Tunnel length and energy per year (in kWh) for 2014 and 2015	17
Netherlands (Rijkswaterstaat)	Tunnel length and energy per year (in kWh) for 2006 and 2009, and detailed energy splits for different tunnel features	13

The data collected was for 90 tunnels in excess of 500 m long, covering an aggregated bore length in excess of 383 km. The breakdown of the tunnel ‘types’ is presented in Table 2-2. The data did not allow for separation of the NATM / TBM types.

Table 2-2: Tunnels included in the REETS dataset

Tunnel type	**Number of tunnels**	**Total length (m)**
Cut & cover	14	34,667
NATM / TBM	59	307,772
Immersed	13	32,067
Partly covered / Gallery	4	8,610

2.2 The potential for energy reduction

Considering the life cycle of a tunnel allows a picture of its overall energy consumption to be built up. On a life cycle basis, energy consumption can be classified into three main elements: construction and maintenance (but not including major upgrades); operation; and use.

A large quantity of energy is expended during construction and periodically throughout the life cycle during maintenance/refurbishment. Tunnels have a long working design life; 100 or 120 years is usual, though in practice a tunnel may be in service for longer.

During this lifetime, to keep the tunnel operational for road users, energy is expended to keep the tunnel lit, ventilated and drained. Given the long operational lifetime, the total energy expenditure mounts up considerably.

A significant portion of life cycle energy consumption is associated with the energy expended by vehicles travelling through the tunnel. This energy consumption is significant although its link to the tunnel/road operator is rather indirect.

2.2.1 Elements of energy consumption

<u>Construction and maintenance</u>

Much of this energy expenditure is committed as fuel used in excavation or construction of the tunnel lining and associated structures. Furthermore, a considerable amount of energy is embodied in the material used to construct the tunnel. Two life cycle assessment (LCA) studies have quantified this element of energy consumption.

The first was conducted in Norway by Huang *et al*. [6] who evaluated the environmental impacts of a 'standard Norwegian road tunnel' constructed using the Drill and Blast (D&B) method. The tunnel was 3 km in length and had a 67 m^2 cross section. Around 6.5 tCO_2 equivalent (CO_2e) could be attributed to construction of a 1 m length of the tunnel, with a further 2.0 tCO_2e attributed to maintenance over a 100 year lifetime. Two key points should be noted: firstly that the D&B method is suitable only for tunnels constructed through competent rock and that these tunnels require little, if any, tunnel lining after excavation (and therefore incur minimal further embodied carbon costs associated with tunnel lining materials). Secondly, the CO_2e intensity of Norway's electricity generation compared to the rest of Europe is low (0.141 $kgCO_2e$ per kWh compared to 0.431 $kgCO_2e$ per kWh, including transmission and distribution losses and well-to-tank impacts; [7]). Across the 20 km of tunnels that are constructed annually in Norway, 57 % of CO_2e generated is attributed to the embodied carbon in materials, 16 % to diesel use in construction, 16 % to electricity use in construction and 11 % to transport of materials and waste. Taking this into account, and increasing the CO_2e of electricity consumption to the EU average would arrive at a figure of 11.2 tCO_2e per metre of tunnel or approximately 17,300 kWh total direct energy use per metre.

The second LCA was conducted in the Netherlands by Miliutenko *et al*. [8]. This study was based on the Swedish tunnel 'Norra Länken' that included a 7.5 km long bore of rock tunnel and a 2.5 km concrete lined bore. This LCA calculated impacts associated with the rock bore to be 4.8 tCO_2e per lane-m of tunnel or 27,800 kWh in cumulative energy demand (CED). For the concrete lined section the equivalent figures were 22.1 t CO_2e per lane-m of tunnel or 72,200 kWh in CED. Scheduled maintenance and refurbishment (but not including major enhancements) over the 100 year design lifetime would generate a further 1.9 tCO_2e per lane-m of tunnel or 11,700 kWh of CED for both types of tunnel.

<u>Operation</u>

Annual energy consumption figures were provided by the operators for each of the tunnels included in Table 2-1 and used to derive the mean energy consumption per metre length as provided in Table 2-3. Some considerable variation was observed in the figures; therefore, averages based on the middle two quartiles of the ranges are also presented.

Table 2-3: Mean energy consumption per metre of tunnel, by type of tunnel

Tunnel type	Mean energy consumption (kWh/m)	Mean based on 2nd and 3rd quartiles (kWh/m)
Cut & cover	297.3	290.0
NATM / TBM	193.2	195.3
Immersed	1001.6	1094.9
Partly covered / Gallery	287.6	183.2

Figure 2-4 shows the trend in energy consumption for each tunnel 'type'.

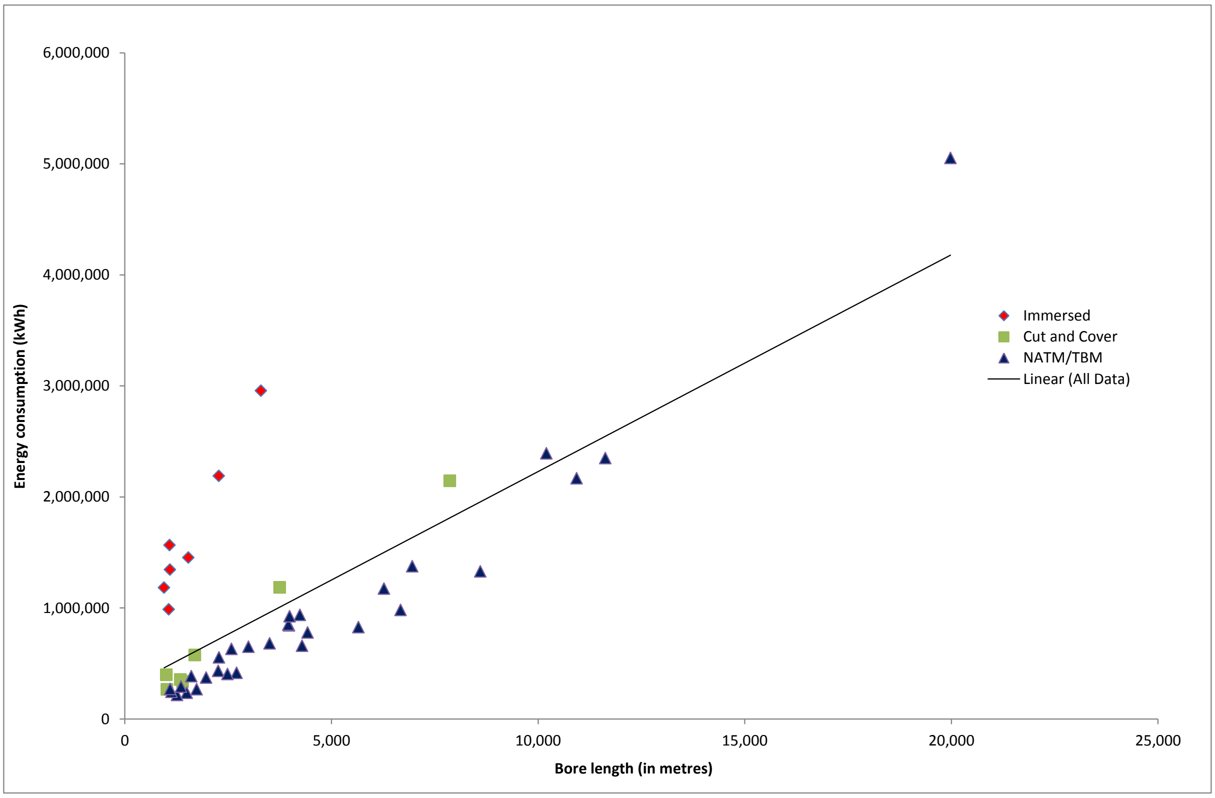


Figure 2-4: Relationship between energy consumption and bore length, for the 2nd and 3rd quartiles

The mean values provide baselines from which the potential for energy reductions can be determined.

The data for the 13 tunnels from the Netherlands [5] allowed overall energy consumption to be allocated to the separate services required to keep the tunnel functioning: Figure 2-5 shows the means of these splits. It is important to note that these data are based on varying technology levels. For example, some tunnels may have already deployed LED lighting whilst others may still use high pressure sodium lighting.

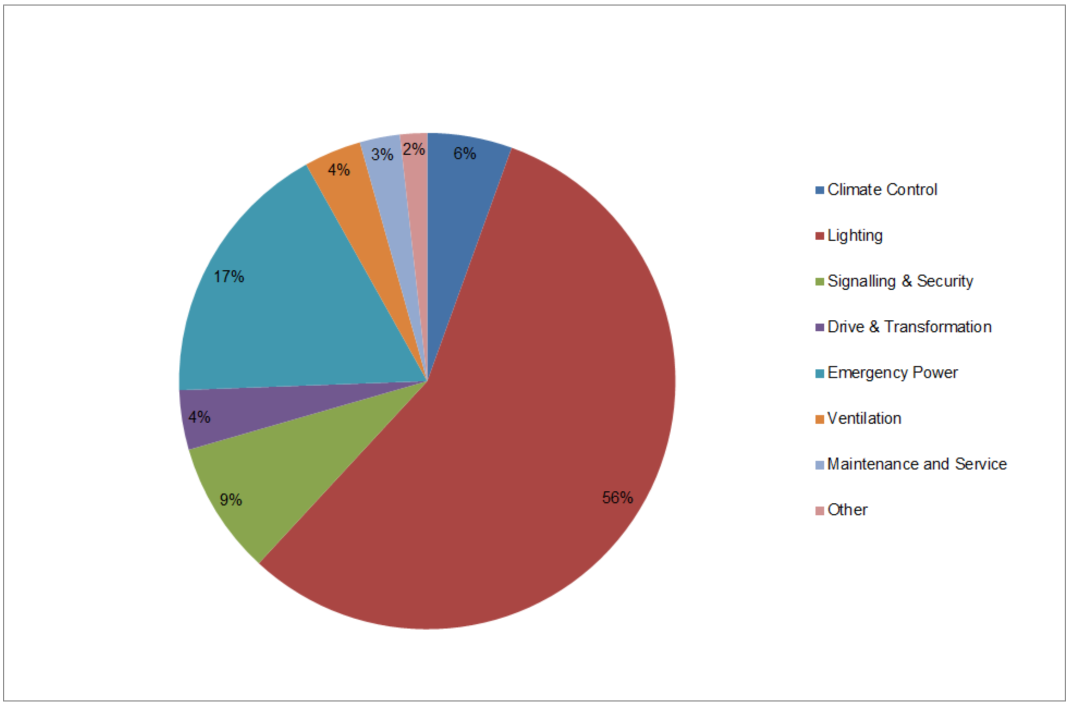


Figure 2-5: Operational energy demands of different tunnel services

Lighting and emergency power dominate the operational energy demands. This infers that that the greatest gains in energy efficiency might be achieved by deploying technologies that address the provision of energy itself (i.e. more efficient delivery of energy), or address lighting specifically.

<u>Use of the tunnel</u>

Another main component of energy use in tunnels can be attributed to vehicular traffic using the tunnel. This component of energy consumption is included since, to some extent, it can be influenced by traffic flow measures deployed within the tunnel and by driver-based technologies promoted by tunnel operators or NRAs. The calculation of energy use by vehicles can be derived from emissions factors; in this case an emissions factor toolkit devised by the UK's Department for Transport [9] has been used to provide estimates for a range of annual average daily traffic (AADT) levels: see Figure 2-6. The estimates are based on a 1 km motorway length, with 5 % heavy goods vehicles, and a speed limit of 110 km per hour. Energy use can be derived from the CO_2 figures by, for example, assuming 50 % of emissions arise from diesel consumption and 50 % from petrol consumption.

Figure 2-6: Mean vehicle emissions for a 1 km length of motorway

Mean annual average daily traffic (AADT)	**CO_2 emissions per annum (t/km)**	**Annual energy consumption (kWh/km)**
5,000	363	1,255,703
10,000	726	2,511,406
20,000	1452	5,022,812
50,000	3631	12,557,030
100,000	7262	25,114,060

2.2.2 *The overall picture of energy consumption*

The three main components of energy consumption can be considered together to provide an overall picture of consumption for two hypothetical tunnels. The first case, a five kilometre, single bore tunnel constructed using the D&B method has an AADT of 5,000 vehicles. The second case considers a two-kilometre, twin-bore concrete box immersed tube with an AADT of 50,000 vehicles and two lanes in each bore. Both tunnels are maintained for a 120 year service life. The energy consumption of the two tunnels is shown in Figure 2-7 and Figure 2-8.

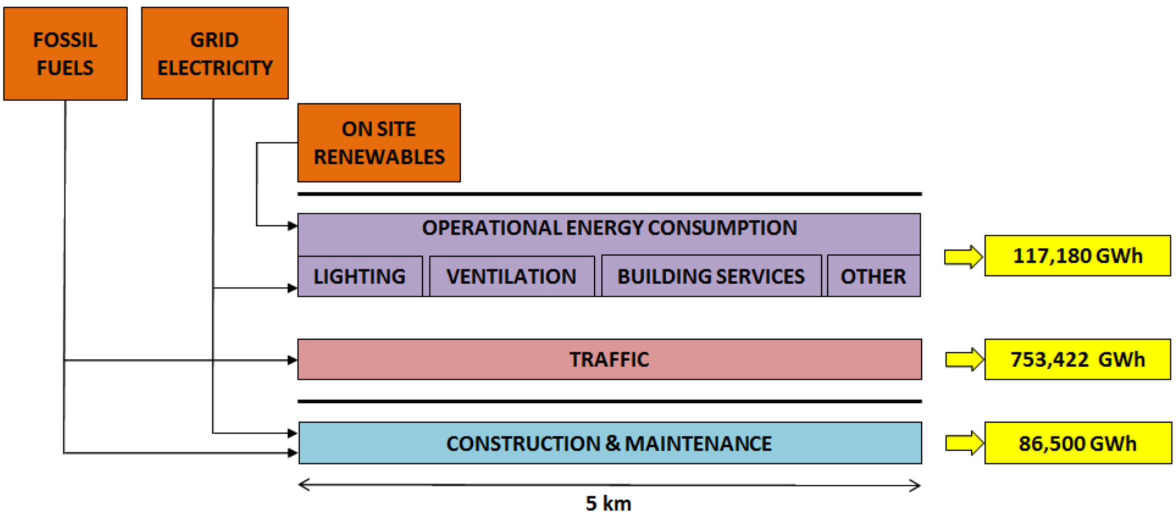


Figure 2-7: Energy consumption over the 120 year lifetime of a single bore, 5 km D&B road tunnel

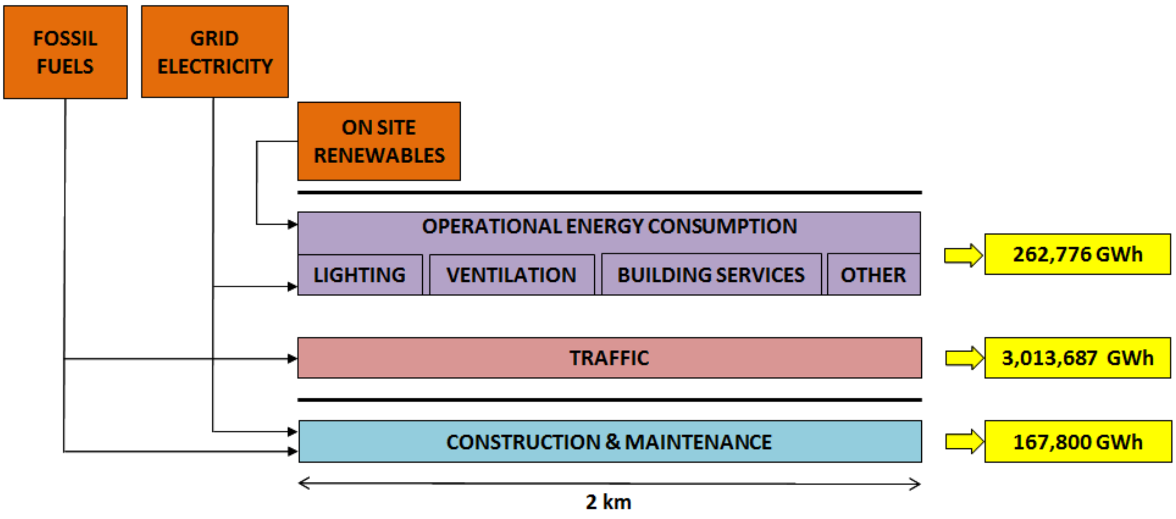


Figure 2-8: Energy consumption over the 120 year lifetime of an immersed, twin bore, 2 km road tunnel

The results of the two scenarios highlight (expectedly) the significance of vehicle energy use in the overall life cycle picture. Tunnel operators (or NRAs) have the least influence over this component of energy use, but their aim should be to promote smooth traffic flow, to avoid traffic queues and stop-start driving that gives rise to lower energy efficiency and higher tailpipe emissions. To some extent the decision to construct a tunnel may have already been made to avoid significant levels of tailpipe emissions associated with a longer surface road route. Energy use in relation to construction and maintenance in this overall life cycle is surprisingly high; however, there are few options once the decision to build a tunnel has been made, since the type of construction has to suit ground conditions to achieve the desired level of safety and longevity in the build. Of broadly equal significance to construction is operational energy use. This is the component that has the most scope for improvement through the deployment of suitable technologies. It is also the component that NRAs potentially have the biggest influence over.

The remainder of this report considers, in depth, a shortlist of the most promising technologies that can be used to address operational energy use.

3 Assessment of technologies

3.1 Description of technologies

3.1.1 Reducing tunnel threshold luminance

The objective of tunnel lighting is to allow users to enter, transit, and exit a tunnel in comfort and at a level of safety that equals (if not exceeds) that of the open road. The guidance for tunnel lighting in national standards varies in detail, but all states that the amount of lighting required within a tunnel depends on the level of light on the tunnel approach, and inside the tunnel to allow the driver's eyesight to sufficiently adjust.

The aim of this technology is to reduce the required lighting level in the threshold zone which, in turn, determines the lighting levels in other zones within the tunnel. The access zone of a tunnel is part of the approach to the tunnel and is defined as being equal in length with the 'stopping distance' (see Figure 3-1). In the first part of this area, the required luminance should be constant and is determined by the L_{20} value.

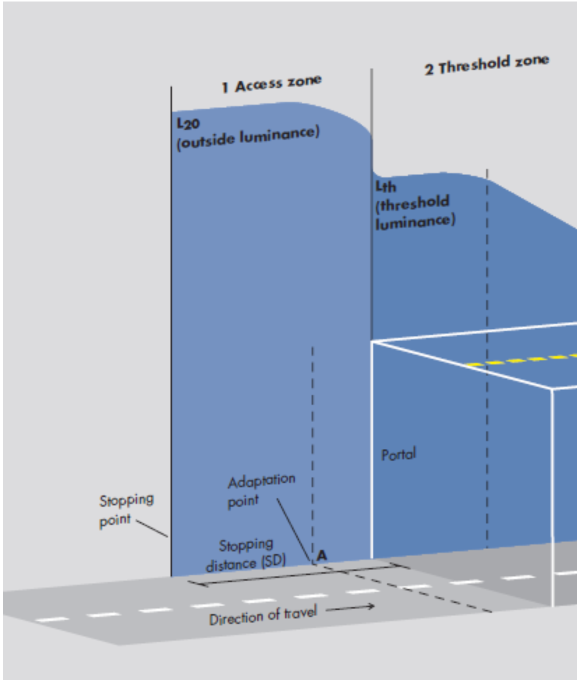


Figure 3-1: The access and threshold zones of a tunnel approach [10]

Drivers should be able to see clearly into the tunnel to detect any obstacles and react safely, instead of being confronted by an area with much reduced visibility. Generally, the lighting of a tunnel is divided into zones (see Figure 3-2):

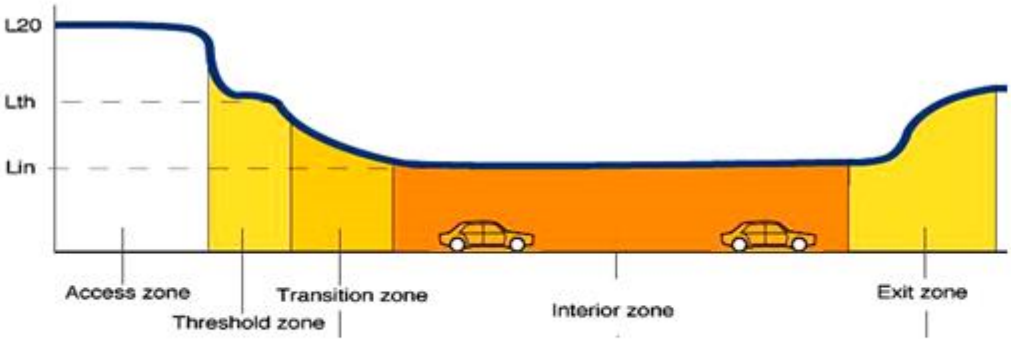


Figure 3-2: Visualisation of tunnel zones

<u>Access zone</u>

The access zone is formed by the approach road itself. The L_{20} method considers the ambient lighting from the environment (e.g. sky, and road surface) by determining the tunnel's portal luminance from the stopping distance via a 20° conical field of view on the line of sight of the driver from the beginning of the access zone. This is the fundamental characteristic needed for deriving the lighting requirement within the tunnel.

Threshold zone

The first zone in the tunnel itself is the threshold zone, which extends for the same length as the stopping distance for the design speed of the approach road. The target luminance level L_{th}, for this zone is derived from the L_{20} value factored for the class of tunnel. This level is maintained at 100 % for the first half of the threshold zone and reduces to 40 % by the end of the zone.

Transition zone

The transition zone extends from the threshold zone to the point at which the specified daytime interior zone level is reached. Throughout the transition zone, the luminance levels are gradually reduced at a rate conforming to the CIE reduction curve (Figure 3-3), to enable the human eye to accommodate to the continuing lower lighting levels. The length of the transition zone is dependent on the design speed of the road.

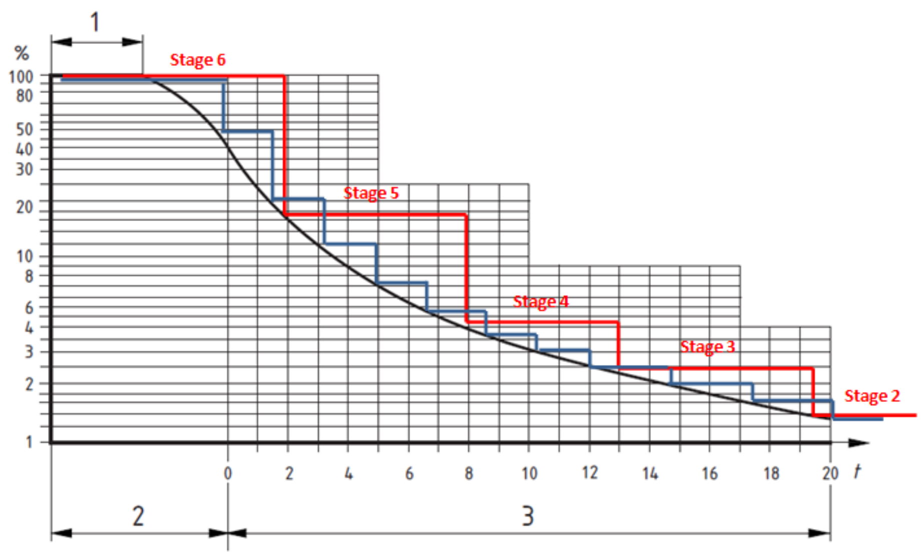


Figure 3-3: CIE Reduction curve (lighting stages superimposed)

Interior zone

During the day, the interior zone stretches from the end of the transition zone to the beginning of the exit zone. The lighting levels L_{in} required in the interior zone will be scheduled in the appropriate standard for the characteristics of the tunnel use. At night-time, the interior zone stretches along the whole length of the tunnel.

Exit zone

The exit zone normally stretches for a distance in metres equal to the speed of traffic in kilometres per hour (e.g. 50 km/h – 50 m) with a luminance level of five times that of the interior zone. The eye adapts much more quickly to increasing lighting levels than to decreasing levels. Exit lighting assists rear vision as vehicles leave the tunnel, as well as preventing smaller vehicles being hidden behind trucks in the tunnel against the bright exit portal.

The lower the L_{20} value, the lower the luminance in the threshold zone. The installation of screens or taut structures at the tunnel portal is intended to provide threshold lighting from natural light as opposed to artificial means. Therefore the tunnel is effectively extended by such screens or taut structures (see Figure 3-4).

Figure 3-4: Fixed structure at Kingsway tunnel (Google Street View)

The structure itself requires energy input to manufacture and, therefore, embodies a quantity of carbon. This embodied carbon should be traded-off against any savings that the structure could deliver through the reduction in lighting requirements over its lifetime.

3.1.2 LED lighting with 'closed loop' feedback

LEDs are already widely deployed in tunnels. Current installed LED schemes utilise dimming and switching processes to achieve variable lighting levels required for different zones of a road tunnel (see Figure 3-5).

The dimming or switching process is usually controlled by a photometer, which is a sensor located at the stopping distance in front of the tunnel portal that constantly records the varying L_{20} values from the sight distance (SD) throughout daylight hours. The output from the photometer is processed through a controller that energises the boost lighting luminaires within the tunnel to the levels required.

Figure 3-5: LED lighting system [11]

The proposal is that, through utilising closed-loop feedback, lighting levels could be matched to the current actual environmental conditions more closely, therefore avoiding over or under lighting the tunnel using less adaptive (e.g. manual) methods or constant, unchanging levels.

Carbon savings can be elicited from use of more efficient, adaptive lighting regimes, than ones that provide constant levels.

3.1.3 Integrated tunnel monitoring systems

The systematic monitoring of operational and maintenance activities is essential for operating a tunnels throughout its service life.

Monitoring can help to maintain the required safety levels and improve day-to-day operation and maintenance of tunnels. Currently, tunnels are equipped with multiple monitoring systems, such as: closed-circuit television (CCTV); lighting; ventilation; incident detection; traffic control; energy; and communications. All these systems employ various sensors or sub-systems to monitor the environment of the tunnel using equipment such as cameras, fiber optics, variable message signs, fire detection systems, emissions detectors and luminance meters (see Figure 3-6).

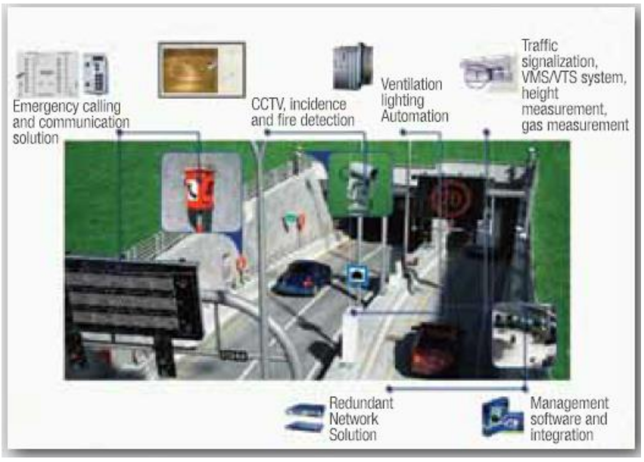


Figure 3-6: Tunnel monitoring system [12]

The proposal would integrate all the monitoring systems into a single management system. By virtue of having the system installed, and through use of the data generated, tunnels can be run more efficiently and use less energy. The data the systems produce can detect early performance degradation in a timely manner and, thereby, limit the risk associated with engineering failures which could compromise the safe operation of the tunnel.

The use of meters to directly monitor energy consumption - at frequent intervals and sufficiently disaggregated to specific functions - can in itself have a positive impact, not least by providing a baseline that can be exploited to reduce energy consumption. This is the philosophy behind the rollout of ‘smart’ meters to domestic energy users in many countries [13]. The equivalent technology for non-domestic users in the UK is ‘advanced metering’. Through controlled trials undertaken by the Carbon Trust, advanced metering delivered up to 12 % electricity savings on SME sites [14]. The ‘lower benefits’ scenario delivered a 4 % saving.

3.1.4 High voltage distribution incorporating voltage optimisation, dynamic UPS and avoiding dynamic oscillation

The network of transmission and distribution used to deliver electricity commonly utilises low voltage systems; however these can be subject to losses that affects the overall performance [15]. The aim of this proposal is the adoption of high voltage distribution systems. These have a number of potential advantages over low voltage systems: they can provide a more reliable power supply and, thereby, reduce energy losses and improve energy efficiency. Insulated overhead cable systems can be used in combination with high voltage distribution systems to help eliminate the faults associated with low voltage systems [16].

Voltage optimisation is targeted by certain technologies to regulate incoming power and match the voltage supplied with that required by the electrical equipment. A further innovation diverts energy saved into a storage system, which can be used when needed. The advantages of voltage optimisation include reduced electricity costs and CO_2 emissions. The University of Surrey delivered over 185,000 kWh savings in annual electricity consumption using the Powerstar system (Figure 3-7), equating to savings of 8 % with a payback period of just over three years [17].

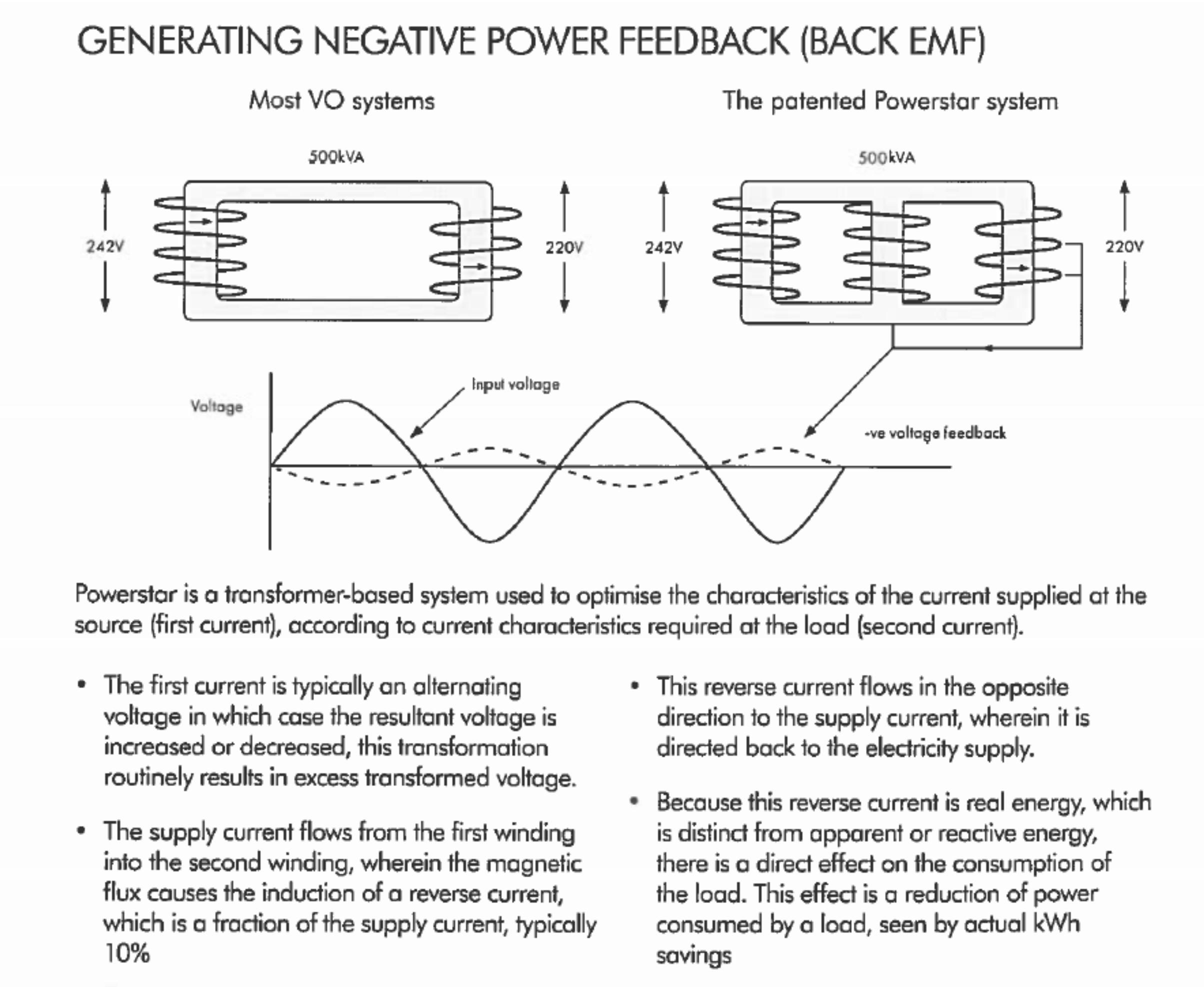


Figure 3-7**:** Powerstar voltage optimisation system [17]

Uninterruptible power supply (UPS) can provide emergency power for electrical equipment when the input power source fails. A broad outline of a UPS system is represented in Figure 3-8. All UPS systems aim to store power through a flywheel or battery [18]. The use of efficient UPS systems enables tunnel safety systems to operate in the event of a major power failure and also provide a limited amount of tunnel lighting. UPS systems can provide continuity, consistency and reassurance; they can pre-empt any issues by switching to alternate power when anomalies such as surges, spikes or dips occur [18]. UPS systems have a short payback time of a few years.

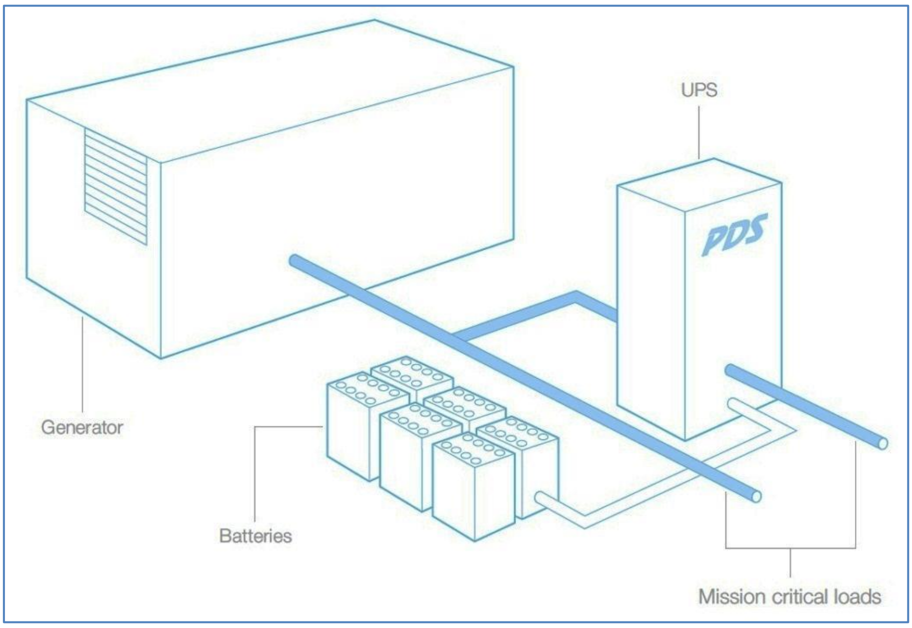


Figure 3-8: Outline of a UPS system [19]

Technologies are also available to reduce dynamic oscillation of the power supply. Power system stabilisers provide damping for low frequency modes of oscillation to enhance the dynamic performance of the supply during post-fault conditions [20].

3.1.5 Incentivising energy efficiency

Through procurement and imposing contractual conditions, NRAs have the ability to incentivise the efficient use of energy in assets operated on their behalf. The overarching aim of NRAs should be to have a sustainable assets; from an economic, environmental and societal point of view. To achieve this, procurement strategies promote purchase of equipment with the lowest whole life cost (assessed from purchase to disposal), the lowest environmental impact, and the lowest risk (to road users, road workers, etc.). This could be achieved through:

- Using commercial 'off the shelf' products (COTS), resulting in lower production and maintenance costs, and improved reliability, thereby increasing safety and service lifetime.
- Procuring a price/quality ratio that reflects the ratio of purchasing and running costs versus maintenance and operating costs.
- Evaluating potential alternative products for the same function with a procurement scoring system that evaluates both price and quality.
- Reflecting whole-life costs in the price element.

Once a product is installed, there is little that can be done to make it more energy efficient. By adding the energy costs to the initial product cost, the supplier would focus more on reducing total energy costs. The suppliers are in the best position to reduce whole life energy costs. A stepwise approach to lower overall energy use is often desired. This can be encouraged by requiring suppliers to avoid unnecessary energy use or switching to more energy efficient technologies through financial reward and/or recognition in tender assessment processes.

The overall utilisation of equipment should also be considered, since targeting low use equipment will only provide low reductions in energy use. For example, a pump might be activated only a few times per day when sump levels reach a certain level, whereas lighting in the interior zone of the tunnel might be operational 24 hours a day, 365 days per year.

Tariff selection should also be carefully considered at the outset of a project, to match the anticipated electrical demand to the correct tariff. Usually, in the UK, once the electrical demand capacity is set it remains in force for a period of 5 years, and payment is levied against the client on a monthly basis. If demand is overestimated at inception stage then this could result in payments for electricity that is never used. Tariff selection could therefore be used as an incentive for the host provider to suggest tariffs based on reliable assumptions and estimates, and ultimately making the correct selection could be rewarded retrospectively. Data from previous projects should be used to determine a ‘realistic’ capacity,

A ‘carrot and stick’ ethos could be instigated with contractors and operators. This could be achieved by the formulation of a ‘target energy consumption’ figure for the tunnel. As no standard target energy exists for these types of assets, the design team in conjunction with the client would be tasked with agreeing such a figure. The proposal would be that, once agreed the contractor would be penalised if a higher energy use is realised, but rewarded for lower-than-target energy usage.

Usually, the up-front purchase cost is the most significant element of procurement strategies used to select equipment. A more holistic procurement strategy would include some/all of the elements described above. A modified Design, Build and Finance of the Operation (DBFO) approach could also be considered. DBFOs typically penalise the operating contractor if the road/tunnel is not available for the general public. If the penalties and gains were extended to cover the amount of energy, this should produce efficiencies in energy use.

3.1.6 Baselines and modified scenarios

To assess whether or not an energy efficient technology is effective or not, the scenario in which the technology has been deployed needs to be compared against a baseline or ‘business as usual’ scenario. This allows for comparisons to be made and the true benefits (or burdens) of the modified scenario to be elicited. For each of the technologies described above, a baseline and a modified scenario with the energy efficient technology deployed have been suggested in Table 3-1.

Table 3-1: Baseline and modified scenarios

Shortlisted technology	Baseline	Modified scenario
Reducing threshold luminance with fixed screens	No daylight dimming prior to the tunnel entrance. A full artificial lighting requirement in the threshold zone.	Tunnel entrance covered with screens to achieve daylight dimming. Threshold zone lighting requirement consequentially lower.
LED lighting with 'closed loop' feedback	LED lighting with conventional photometer sensors recording L_{20} values and adjusting boost lighting levels in threshold, transition and exit zones.	LED lighting with dynamic close controls aligning boost lighting levels to those required.
Integrated tunnel monitoring systems	Separate monitoring for different tunnel systems.	An integrated system monitoring all elements of energy consumption.
High voltage distribution incorporating voltage optimisation, dynamic UPS and avoiding dynamic oscillation	Electricity supplied at conventional voltage using conventional transformers.	(a) Electricity supplied at fixed voltage output from secondary side of transformer voltage, or (b) low voltage side dynamic voltage optimization.
Incentivising energy efficiency	No financial incentives to achieve energy efficiency in procurement. Least expensive technologies deployed with low energy efficiency.	Procurement encourages deployment of highest efficiency motors for ventilation fans with added capital costs. Proportion of cost savings achieved through lower energy consumption can be passed on to DBFO contractor.

3.2 Assessment methodology

The proposed assessment methodology has four components:

i. Carbon
ii. Cost
iii. User safety and comfort
iv. Technological readiness level

3.2.1 Life cycle carbon and cost

The scope of this project does not extend to a full life cycle assessment (LCA) for each shortlisted technology. However, a streamlined life cycle approach can be used to evaluate the key trade-offs associated with each technology and provide an indication of the magnitude of the overall carbon impact, whether positive or negative. A good deal of data from previous LCAs can be utilised within this framework.

The basic premise of such a method is represented in Figure 3-9.

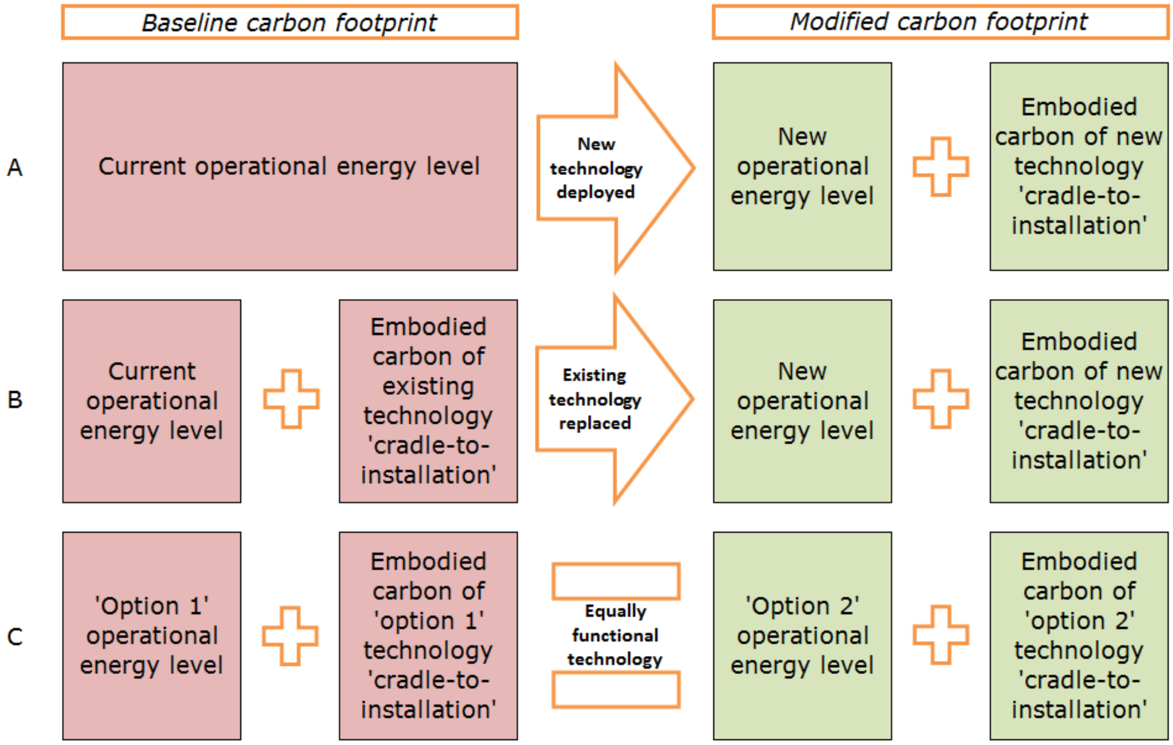


Figure 3-9: A streamlined methodology to assess trade-offs

Figure 3-9 shows three variations on a streamlined carbon footprinting approached that can be tailored, as required, to the particular technology.

Option A would be appropriate to evaluate a completely new technology deployed to modify energy consumption, above and beyond what is already deployed. This type of approach will be used to evaluate threshold screens, integrated tunnel monitoring systems and voltage optimisation solutions.

Option B is appropriate to evaluate a technology that replaces another, for example the adaptive LED controls replacing the current solution.

Option C is appropriate to use where two technologies of equivalent function can feasibly be deployed in place of one another at the same point in time. If the technologies are similar in build then the embodied carbon can be discounted as a ‘common denominator’ and operational energy consumption levels can be compared in isolation.

The likely replacement rates for each of the technologies are also significant. These can be used to determine how many times the equipment needs to be replaced over the service lifetime of the tunnel. Some indicative values are provided in a PIARC publication [21] and these have been used for the analysis (presented in Figure 3-10).

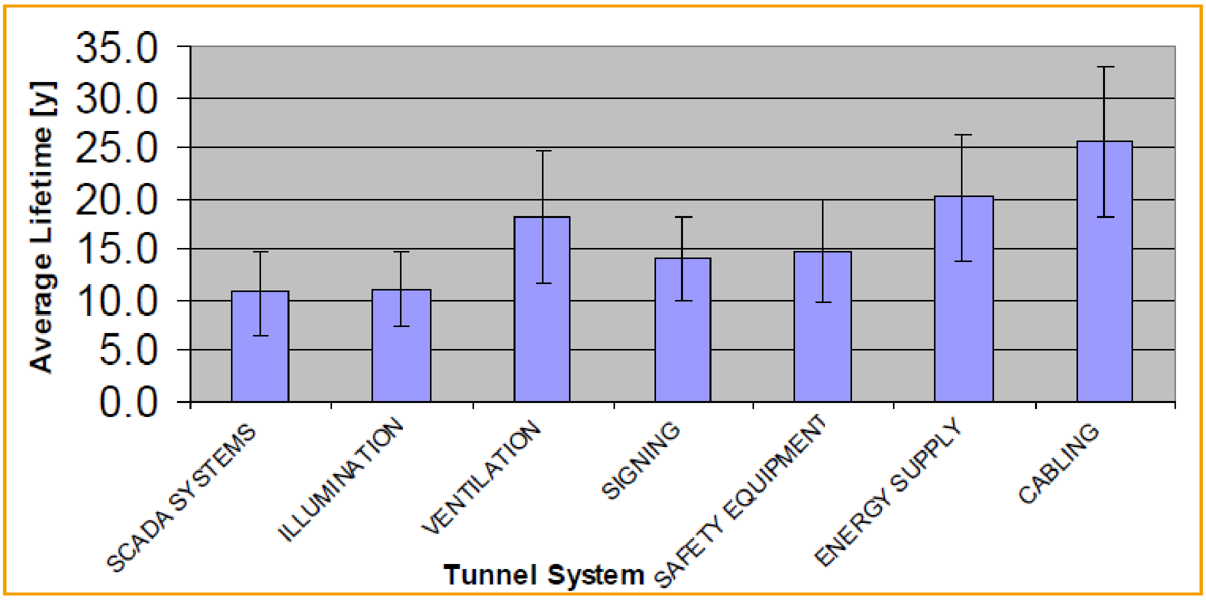


Figure 3-10: Indicative lifetimes for tunnel systems (reproduced from [21]

In this streamlined assessment, the traffic impacts associated with temporary lane or tunnel closures to undertake maintenance interventions are not included. Costs can be evaluated using an approach similar to the carbon methodology; options A, B and C are all valid for a cost analysis approach. The time value of money is not taken account of in the method.

3.2.2 User safety and comfort

The principal aim of the five shortlisted technologies identified is to provide potential energy reductions for road tunnels. Nevertheless, it is paramount that the level of safety and comfort for tunnels users are not reduced: indeed there would be benefit in improving such levels.

The investigation on user safety and comfort was performed in a qualitative manner. Therefore, various methodologies employed in previous and current CEDR European projects, such as RAIDER [22], COBRA [23] and PRIMA [24] were reviewed, to identify the most appropriate quality indicators needed in the context of tunnel safety.

The indicators used to assess user safety are:

- Reduction of personal injury accidents.
- Reduction of fatally and seriously injured (FSI).
- Reduction of speeding.
- Reduction of speed variation and smoothing of traffic flow.
- Reduction of incident detection time.

The indicators used to assess user comfort are:

- Influence on visibility of tunnel features.
- Influence on driver distraction, defined as any activity or object that diverts the driver’s attention from the task of driving.
- Influence on blending level, defined as the ability of the driver to distinguish between fixed tunnel elements such as road markings or the curvature of a wall.
- Influence on visibility of moving objects such as vehicles, road workers, etc.
- Influence on air quality.

- Influence on subjective safety.

The scale used in the assessment was:

- "-" meaning negative
- "0" meaning neutral
- "+" meaning fair
- "++" meaning positive

In terms of technological readiness, the TRL scale employed by the European Union for the Horizon 2020 Framework programme shown in Figure 3-11 was used: this took account of the extent of current deployment of each of the investigated solutions.

TRL Scale	Description
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technological validity in a lab
TRL 5	Technology validated in relevant environment
TRL 6	Technology demonstrated in relevant environment
TRL 7	System prototype demonstration in an operational environment.
TRL 8	System completed and qualified
TRL 9	Actual system proven in operational environment

Figure 3-11: TRL scale, as used by the EU [25]

3.3 Definition of model inputs

A number of input variables were required to complete a quantitative assessment of whole carbon and life cycle cost. These are defined below for each of the shortlisted technologies.

3.3.1 Reducing threshold luminance with fixed screens

To assess the potential of this technology, a baseline tunnel scenario was defined:

- An existing two bore, twin lane, submerged tube.
- A speed limit of 80 km/h.
- A sight stopping distance of 100 metres.
- The target luminance required for the first half of the threshold zone was 340 cd/m^2 at 100 %, determined from the tunnel portal evaluation.

The lighting stage control principle was first introduced in 3.1.1. The stages are accumulative, i.e. Stage 1 – night time lighting is always on, Stage 2 is on from dawn to dusk, both normally controlled by sensors. At Stage 6 all luminaires are energised. From Stage 3 onwards, the lighting is controlled by external photometers that measure the L_{20} throughout the day, which calling for the appropriate stage. It should be appreciated that the “Boost” lighting operations can vary year to year, depending on tunnel orientation (in relation to the sun’s transit) and site conditions (local weather conditions). The peak boost lighting may shift pre/post midday dependent on the orientation of the portal and the sun’s transit.

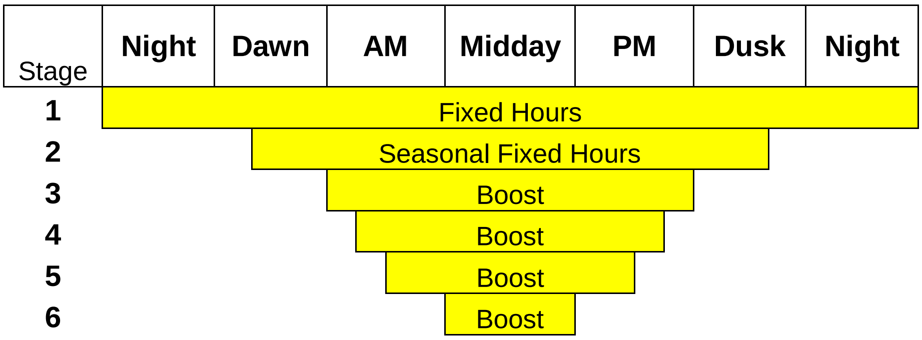


Figure 3-12: Lighting stage control operation (own source)

The tunnel luminaire arrangement that was taken as the sample for evaluation is described in Table 3-2. Only the threshold entrance area of a tunnel was considered (SD x 0.5). There are four rows of luminaires, consisting of 2 x 58 W fluorescent models for the night and basic day lighting requirements, as well as 400 W HPS (High Pressure Sodium lamps) used for all boost lighting requirements.

Table 3-2: Sample of tunnel luminaire arrangement

	Lamps per stage					
SD x 0.5 (Constant Level)	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Row 1: 20off 2x400 W HPS			7	13	20	
Row 2: 20off 2x58 W TL	20	20				
Row 3: 20off 2x400 W HPS			7	13	20	
Row 4: 20off 2x400 W HPS						40

Table 3-3 and Table 3-4 show a comparison between the energy consumption and costs associated with a tunnel without screens and a tunnel where entrance screens were installed, subsequently extending the tunnel and providing for luminance requirements in the first half of the threshold zone (SDx0.5). This evaluation is applicable for both screens and taut structures giving light transmission performance in the region of 10 %.

Table 3-3: Existing installation without entrance screens installed (per entrance)

	Installed Watts per Row				**Total per stage**	**Accum Stage Load**	**Estimated Annual**	**Estimated Annual**	
St	R1	R2	R3	R4	**(kW)**	**(kW)**	**(Hours)**	**(kWh)**	
6				17,800	17.8	55.92	240	13,421	
5	8,900		8,900		17.8	38.12	600	22,872	
4	5,785		5,785		11.57	20.32	980	19,914	
3	3,115		3,115		6.23	8.75	1,100	9,625	
2		1,260			1.26	2.52	1,460	3,679	
1		1,260			1.26	1.26	4,380	5,519	***Energy Cost***
					55.92		**8,760**	**75,029**	€0.12
								Cost per year	€9,003.53
								At 120 Years	€1,080,423.36
								Per tunnel (twin bore)	**€2,160,846.72**

Table 3-3 depicts the installed luminaire arrangement. Row 2 is the night and basic day fluorescent luminaires energised on stage 1 (night) and stage 2 (day) respectively. Rows 1, 3 and 4 are the boost lighting HPS luminaires energised from stage 3 onwards. Power values are that of the total lamp circuits and so include any losses. From Figure 3-12, the annual energisation hours have been estimated for this typical installation to give the total annual kilowatt hours. Energy cost was taken at €0.12 per kWh [26]. Accumulating the annual load over an anticipated 120 year service life for a twin-bore tunnel resulted in a lighting cost of €2,160,843. Note that the annual boost lighting load could fluctuate according to prevalent local weather conditions.

Table 3-4: Existing installation with entrance screens installed (per entrance)

	Installed Watts per Row				**Total per stage**	**Accum. Stage Load**	**Estimated Annual**	**Estimated Annual**	
St	R1	R2	R3	R4	**(kW)**	**(kW)**	**(Hours)**	**(kWh)**	
6					0	2.52		0	
5					0	2.52		0	
4					0	2.52		0	
3					0	2.52		0	
2		1,260			1.26	2.52	4,380	11,038	
1		1,260			1.26	1.26	4,380	5,519	***Energy Cost***
					2.52		**8,760**	**16,557**	€0.12
								Cost per year	€1,986.84
								At 120 Years	€238,420.80
								Per tunnel (twin bore)	**€476,841.60**

Table 3-4 uses the same installation as in Table 3-3, but assumes that entrance screens or a taut structure has been installed. This effectively would extend the tunnel by SDx0.5 as a minimum. As the light transmission through the screen/taut structure is circa 10 % of the ambient lighting (see Figure 3-13), the lighting requirement for the first half of the threshold zone L_{th} is being met by the transmittal of partial natural daylight. As such no boost lighting is required within this area, but night and basic day time luminaires will be required to be installed throughout the screen/taut structure to cater for the non-daylight periods. Therefore Table 3-4 only includes for this thoroughgoing lighting, which in this case would consist of a single row of 2x58 W fluorescent luminaires. It should be appreciated that nowadays equivalent LED luminaires would more likely be used.

Using the same power and energisation duration as Table 3-3, but only for the fluorescent luminaires resulted in an accumulated 120 year energy cost of €476,842, a substantial €1,684,005 saving for the lighting of the first half of the threshold zones.

An evaluation of another tunnel, Kingsway Tunnel, Liverpool, with screens installed at construction was performed during site surveys in 2014. Figure 3-13 compares luminance levels of the two bore, twin lane submerged tunnel with a common screen structure over both entrance and exit areas. On the figure:

- The black trace indicates the road luminance of the open road outside the screens.
- The red trace shows the road luminance of the road section underneath the screens.
- The green trace is the required luminance level L_{th} for the first half of the threshold zone.

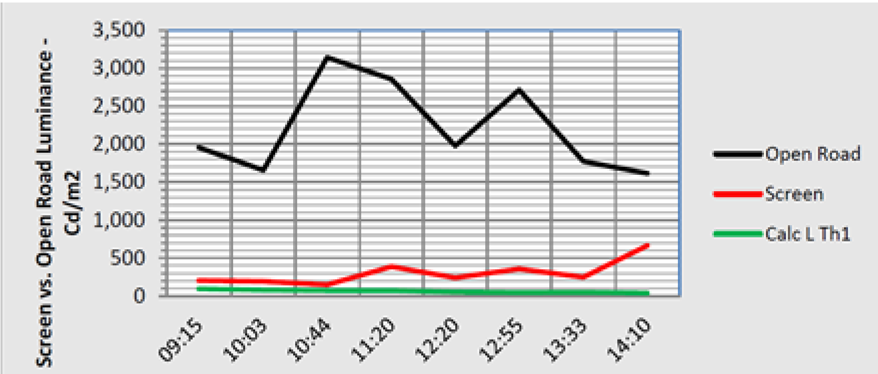


Figure 3-13: Luminance levels in the Wallasey portal of the Kingsway Tunnel

On this basis it would appear that the screens effectively reduce the open road luminance to *circa* 10 % and produce sufficient luminance to effectively provide the required luminance levels for the first half of the threshold zone by natural means.

Shortlisted technology	**Potential energy savings per annum (kWh)**	**Potential carbon savings per annum (tCO_{2e})**	**Carbon savings over 120 yr tunnel service lifetime (tCO_{2e})**	**Embodied carbon outlay of technology (tCO_{2e})**	**Net savings over tunnel lifetime (tCO_{2e})**	**Net cost savings over tunnel lifetime (€)**
Reducing threshold luminance with fixed screens	116,945	50	6,048	602	5,446	892,989

3.3.2 LED lighting with ‘closed loop’ feedback

The ‘open’ loop dimming/switching process for the boost lighting currently used in tunnels is controlled by a portal photometer which constantly records the varying L_{20} values from the SD (sight distance) throughout the daylight hours. The output from the photometer is processed through a dedicated controller PC to energise the boost lighting luminaires within the tunnel to the levels determined according to the characteristics of the tunnel, and are only implemented in specific ‘steps’. This process results in an over-lighting of the boost lighting zones. The actual dimming/switching levels are committed for each stage/zone during commissioning and are, therefore, fixed for the lifetime of the installation.

The proposal for a ‘closed-loop’ feedback is to compare what the photometer registers and calls for - in terms of lighting level - compared to what is being delivered by the installed lighting. A closed-loop, dynamic close-control system would promote the correct level of lighting within the tunnel and, therefore, not over or under light the tunnel.

The interior levels are generally controlled by a PC time-clock for two stages only: daytime and night time. It should be appreciated that the whole length of the tunnel is considered an Interior zone at night (see Figure 3-14). The photometer solely controls the boost lighting in the threshold, transition and exit zones. The implementation of this proposal requires additional photometers mounted within the tunnel boost lighting area, and associated software interface to the control system.

The estimated cost associated with installing photometer(s) and associated software integration is €35,000 per tunnel entrance. This technology could deliver savings c*irca* 10 % of boost lighting energy usage. This technology will replace a pre-existing system so the expenditure is not just ‘additional’ cost.

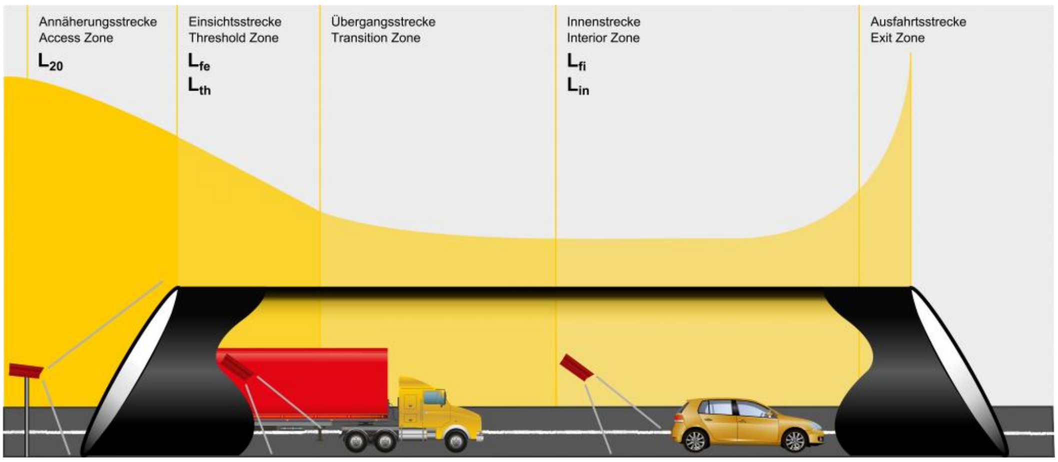


Figure 3-14: Measured luminance in a tunnel and location of photometers [14]

Figure 3-15 shows the lighting reduction curve requirements in the threshold and transition zones, as specified by CIE (International Lighting Commission). Tunnel lighting schemes have to cater for both day and night drivers’ vision in the photopic or mesopic states. The photopic state is when the eye has become fully adapted to lighting levels generally above 3.5 cd/m^2 with the mesopic state being between 0.035 & 3.5 cd/m^2. During the day, the eye’s photopic state when approaching the entrance portal is addressed by the application of the CIE entrance lighting reduction curve.

In Figure 3-15, the red trace shows the coarse ‘step’ switching, where the actual delivered lighting is above the target reduction curve. Anything over the target curve is considered wasted energy, while anything under the target curve would be considered as under-performance. The blue trace shows that by applying a close control in ‘multiple stages’, over-lighting can be reduced. However, with traditional control systems, this solution would increase costs due to the need for additional dedicated stage circuits. LED boost lighting installations with fully dimmable attributes best suited to closed-loop control and would enable the lighting to be controlled closer to the target CIE reduction curve.

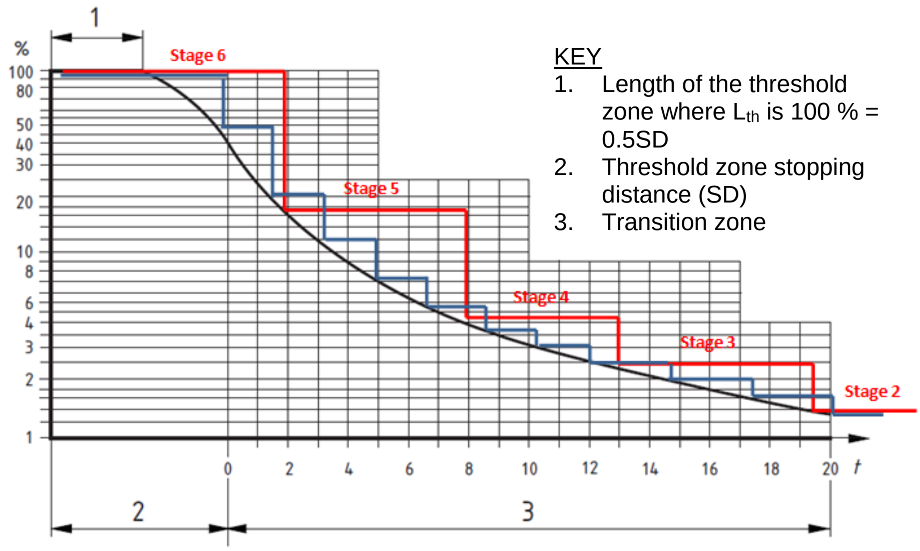


Figure 3-15: CIE Reduction curve (lighting stages superimposed)

The red trace replicates a traditional six stage switching regime for the boost lighting as used for Figure 3-12 and Table 3-3. The blue trace replicates a multiple stage switching arrangement where there is finer control on switching. For the former, the overall energy consumption is presented in Table 3-3; for the latter it is presented in Table 3-5. Direct energy use savings in the region of €189,594 could accrue over the service life of the tunnel through utilisation of this technology.

Table 3-5: Existing installation assuming close controlled, closed-loop feedback (per entrance)

	Installed Watts per Row				**Total per stage (kW)**	**Accum Stage Load (kW)**	**Estimated Annual (Hours)**	**Estimated Annual (kWh)**	
St	R1	R2	R3	R4					
6				17,800	16.02	50.33	240	12,079	
5	8,900		8,900		16.02	34.31	600	20,585	
4	5,785		5,785		10.41	18.29	980	17,922	
3	3,115		3,115		5.61	7.88	1,100	8,663	
2		1,260			1.26	2.52	1,460	3,679	
1		1,260			1.26	1.26	4,380	5,519	***Energy Cost***
					50.582		**8,760**	**68,446**	€0.12
								Cost per year	€ 8,213.55
								At 120 Years	€985,626.14
								Per tunnel (twin bore)	**€1,971,252.29**

In Figure 3-15, the black base trace represents the required target CIE reduction curve with performance achievable by continuous luminaire dimming and compliance provided by a closed-loop feedback control system. There is no wasted energy as the target performance is achieved through feedback.

To realise the direct energy savings, some initial outlay is required in terms of embodied carbon, although this is quite difficult to estimate for specific systems with any degree of accuracy because of the absence of data for particular components (e.g. photometers). A study conducted in the United States by Olivetti *et al*. [27] explored the carbon footprint of four electrical components (motors, energy efficient lamps, electronic and magnetic ballasts, and electrical connectors) by applying a Product Attribute to Algorithm (PAIA) method. The approximate carbon footprints per unit are presented in Table 3-6 (exclusive of the 'in use' impacts).

Table 3-6: Indicative carbon footprints for some electrical components

Component	**Approximate carbon footprint per unit (kgCO_2e)**
Motor	3000
LED (40,000 h lifespan)	4.21
CFL (10,000 h lifespan)	2.24
Electronic ballast (non-magnetic)	15 - 25
Lugs (Cu)	0.1 – 0.3
Lugs (Al)	0.2 – 0.65
Split bolts (Cu)	0.1 – 0.28
Split bolts (Al)	0.07 – 0.5

The total direct energy savings potential equates to 5.67 t per year of CO_2e or 681 t over the lifetime of the asset. Given the values quoted for components in Table 3-6, it is unlikely that equivalent footprints will be much higher for the closed-loop option than for the conventional approach.

Shortlisted technology	**Potential energy savings per annum (kWh)**	**Potential carbon savings per annum (tCO_{2e})**	**Carbon savings over 120 yr tunnel service lifetime (tCO_{2e})**	**Embodied carbon outlay of technology (tCO_{2e})**	**Net savings over tunnel lifetime (tCO_{2e})**	**Net cost savings over tunnel lifetime (€)**
LED lighting with adaptive controls	13,166	6	681	0	681	189,594

3.3.3 Integrated tunnel monitoring systems

The various elements of tunnel services, including lighting, ventilation and mechanical items can be monitored using an overarching system such as a SCADA (Supervisory Control And Data Acquisition) system. The data collected by SCADA systems can attribute energy use to individual tunnel services and therefore determine if they are exceeding their energy target values, and why: it may preclude the failure of a piece of equipment which could precipitate the failure of others. The same data may highlight inefficiencies as the equipment ages in service. The SCADA system could also be empowered to switch and operate items of equipment that might now be a manual operation – electronic switching would reduce the possible overrunning and/or operating period of manually controlled equipment. Constant reviewing of the energy data recorded by a SCADA system may also result in a 'smart metering' effect.

The potential energy efficiency benefits of using a SCADA system can be considered by using a baseline of a one kilometre long, twin bore, multi-lane tunnel with an estimated 1,095,000 kWh annual electrical consumption (see 2.2.2), with lighting that is multi-stage controlled and ventilation controlled by NO_X detectors. Through using SCADA, the potential savings that would result from the forecasting of equipment failures, and also from the potential to remove the human operations from various activities would be 1 %. In addition, 4 % savings might be achieved through 'smart metering' (a mid-range estimate, [14]). These two savings combined would equate to a direct energy saving of circa 23.6 tCO_2e year, based on a figure of 0.431 $kgCO_2e$ per kWh of electricity for the EU-28.

The capital costs of commissioning a SCADA system along with the associated cabling for two kilometres of tunnel are estimated to be in the region of €1,100,000. According to the PIARC estimates in Figure 3-10, a SCADA system would require renewal approximately every 12 years and cabling every 26 years. Over the 120 year lifetime of the tunnel, this would equate to capital costs in the region of €11,000,000 (with no discounting). This far exceeds potential cost savings due to reduced energy consumption, which are estimated to be in the region of €788,400. However, it should be appreciated that tunnel monitoring systems provide several functions, of which energy monitoring just one, and so cost savings realised in terms of avoided accidents and user delays may readdress the balance. It should also be appreciated that €11M reflects the costs to install a full SCADA system from scratch, with all monitoring and detection equipment. In reality, monitoring equipment for some/all services may already exist and just need to be integrated using appropriate IT systems and software. If integration is all that is required then the capital costs of installation should be lower. The case studies that will be conducted for Deliverables 3.1 and 3.2 should give scope to investigate this further.

The picture with regards to carbon savings is far more favourable. Carbon savings per annum due to direct energy savings are circa 23.6 tCO_2e. Over a 120 year lifetime of the tunnel, 2,832 tCO_2e would be saved. Against this some deductions for embodied CO_2e should be made. The Dutch manufacturer SMIT Transformers conducted some product carbon footprints of selected models in their range [28]. Larger transformers were determined to have carbon footprints in the region of 5.1 $kgCO_2e$ per kg of transformer, thus a large transformer and head unit with total mass of two tonnes would have a total footprint of 10.2 tCO_2e, with anticipated replacement every 20 years this would equate to 61.2 tCO_2e over a 120 year period. Armoured cabling would also be required along the length of the tunnel to power the system. Heavy-duty, high specification cabling of the type permitted on UK highways [29] is a composite of copper, medium density polyethylene and steel and is estimated to have a carbon footprint in the region of 27.5 $kgCO_2e$ per metre. Over the lifetime of the tunnel, with replacement every 26 years, the total footprint associated with cabling would amount to 254.4 tCO_2e. The carbon outlay of equipment would amount to just 11.1 % of the potential direct energy savings of the SCADA system.

Shortlisted technology	Potential energy savings per annum (kWh)	Potential carbon savings per annum (tCO_{2e})	Carbon savings over 120 yr tunnel service lifetime (tCO_{2e})	Embodied carbon outlay of technology (tCO_{2e})	Net savings over tunnel lifetime (tCO_{2e})	Net cost savings over tunnel lifetime (€)
Integrated tunnel monitoring systems	54,750	24	2,832	316	2,516	-10,188,138

3.3.4 High voltage distribution incorporating voltage optimisation, dynamic UPS and avoiding dynamic oscillation

A HV/LV transformer is required to convert high voltage (HV) electricity supplied from the host provider or grid into low voltage electricity (LV) for safe use on site. The transformers are required to operate 24 hours a day, 365 days a year, during which time they will undergo constant current and energy losses which can be significant depending on the age and efficiency of the transformer used (Figure 3-16).

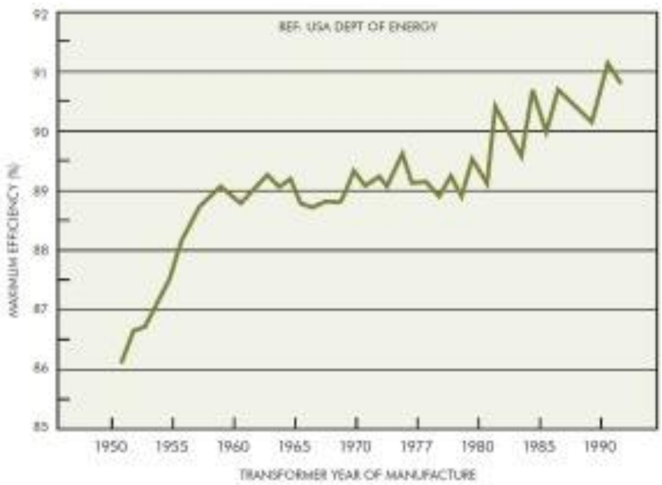


Figure 3-16: Losses within a standard HV/LV transformer

This loss can be defined in two categories:

- On-load losses experienced during the time when electricity is in use.
- No-load losses caused by the load on the transformer regardless of whether electricity is used or not.

The use of high voltage low-loss amorphous based cored transformers in place of oil, cast resin, or midel transformer based units would result in energy savings in the method of construction. In addition to the use of these low loss amorphous transformers, low voltage optimisation units installed and connected on the secondary (LV) side output of the transformer will also result in potential energy savings via the reduction of ‘standing losses’ when the transformer is lightly loaded [18].

These units could also be considered as additional to the existing transformer whatever the type installed. The type of unit required will vary according to the voltage fluctuations on the incoming primary side of the transformer. If the tunnel has a stable incoming high voltage supply then a “fixed” optimisation system may be considered. If the tunnel has a fluctuating incoming high voltage supply then an ‘electronic-dynamic’ optimisation system should be considered. The lengths of cable to be installed with associated voltage drops need to be considered and designers should consider high short duration loads being imposed onto a system; e.g. ventilation units and what effect the voltage regulator would impose on the system operating functions. Designs may need to incorporate ‘smaller’ voltage optimisation units strategically located throughout the length of the tunnel to minimise the effect of equipment failing under extreme voltage drops due to the placement of single units at the origin the installation. Ideally, centralised systems would be adopted and cables sized to minimise the effect.

The optimum solution would be to combine a new low loss transformer and incorporate the voltage optimisation unit within the secondary side connections of the transformer thus reducing footprint area and wiring between the transformer and the stand-alone unit voltage optimisation unit. Ideally, the low operating voltage should be set at 220 V, but care would needs to be taken so that the voltage drops remain in a suitable range (Figure 3-17).

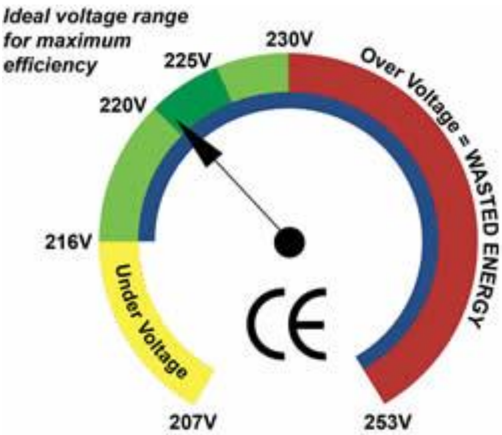


Figure 3-17: Ideal voltage range for maximum efficiency

Utilising the negative power generated from the electronic-dynamic optimisation technology it may be possible to charge an integrated storage system but this level of technology has yet to be proven on a widespread commercial level. However, manufacturers claim that the technology is functioning.

Considering a one kilometre long, twin bore, multi-lane tunnel with an estimated 1,095,000 kWh annual electrical consumption, it is envisaged that the tunnel would have a transformer arrangement to deliver the interleaved supplies. Furthermore it is assumed that the tunnel has transformers nearing the end of their effective service lives. There are two scenarios to achieve voltage optimisation:

- The transformers would be replaced with low loss versions and incorporate integral LV secondary side optimisation. Using the manufacturer claimed savings of 15 %, 70.8 tCO_2e could be saved per annum and service life savings of 8,495 tCO_2e.
- Using the aforementioned estimates from SGB-SMIT transformers [28], embodied carbon to offset would be minimal, at approximately 5.1 tCO_2e per transformer per replacement at 20 year intervals. No additional cabling is anticipated to be required compared to the baseline.
- The existing transformers remain and secondary side optimisation units are installed. Using the average savings from the case studies presented by EMS Powerstar [17], a

potential saving in the region of 11 % could be achievable, equating to a 51.9 tCO_2 saving per annum and 6,230 tCO_2e over the service life of the tunnel.

Shortlisted technology	Potential energy savings per annum (kWh)	Potential carbon savings per annum (tCO_{2e})	Carbon savings over 120 yr tunnel service lifetime (tCO_{2e})	Embodied carbon outlay of technology (tCO_{2e})	Net savings over tunnel lifetime (tCO_{2e})	Net cost savings over tunnel lifetime (€)
Combined transformer and voltage optimization	164,250	71	8,495	61	8,434	745,200
Existing transformer and Low Voltage (LV) side only voltage optimization	120,450	52	6,230	31	6,199	618,480

3.3.5 Incentivising energy efficiency

Higher efficiency motors offer an avenue where there are clear choices and scope for energy efficiency improvements. For example, IEC 60034, defines three classes of efficiency for single speed, three-phase cage induction motors [30]: IE1 (standard); IE2 (high) and IE3 (premium). Shifting from IE1 to IE3 is estimated to deliver a 3.8 % efficiency gain [31]. Several motors of this type might be used to drive ventilation fans in a tunnel. Ventilation accounts for approximately 16 % of the energy consumption in a typical tunnel [5]. Considering the one kilometre long, twin bore, multi-lane baseline tunnel with an estimated 1,095,000 kWh annual electrical consumption, 175,200 kWh can be attributed to ventilation. A 3.8 % efficiency saving delivered on this portion of energy consumption equates to the avoidance of 2.9 tCO_2 emissions per annum: it has been assumed that ten motors are required whether the motors are high or low efficiency.

Shortlisted technology	Potential energy savings per annum (kWh)	Potential carbon savings per annum (tCO_{2e})	Carbon savings over 120 yr tunnel service lifetime (tCO_{2e})	Embodied carbon outlay of technology (tCO_{2e})	Net carbon savings over tunnel lifetime (tCO_{2e})	Net cost savings over tunnel lifetime (€)
Incentivising energy efficiency	6,658	3	344	0	344	77,869

3.4 Assessment results

3.4.1 Quantitative results

The estimated carbon and cost savings of the five technologies are summarised in Table 3-7. As shown in the Table, all five shortlisted technologies are projected to deliver net carbon savings over the service life of a tunnel; with the high voltage distribution and optimisation proposal projected to deliver the highest benefits. Furthermore, all the technologies are expected to deliver cost savings too, except the integrated tunnel monitoring system. However, as previously highlighted, such systems do not only monitor energy use, but also traffic flow and other safety aspects which deliver benefits to offset against the capital outlay. It may also be possible retro-fit these systems to pre-existing monitors and sensors and, thereby, lowering the capital outlay required. The fact that these monitoring systems have a relatively short lifetime of 12 years on average means that the capital outlay is incurred several times over the service life of the tunnel. The principal aim of this report was to consider energy efficiency (with carbon as a proxy) and in that sense all technologies delivered to a greater or lesser extent.

Table 3-7: Estimated benefits of the five technologies

Technology		**Net savings over 120 year tunnel service life**	
		tCO_{2e}	**€**
Reducing threshold luminance with fixed screens		5,446	892,989
LED lighting with adaptive controls		681	189,594
Integrated tunnel monitoring systems		2,516	-10,188,138
High voltage distribution with voltage optimisation	Combined transformer and voltage optimization	8,434	745,200
	Existing transformer and Low Voltage side only voltage optimization	6,168	114,480
Incentivising energy efficiency		344	77,869

The life cycle cost assessment did not consider fluctuation in energy price or inflation. Consideration will be given to these factors in Deliverable 3.1.

3.4.2 Qualitative results

Table 3-8 presents the results of the qualitative assessment of the five identified energy-reducing solutions.

By reducing the luminance requirements in the tunnel threshold area, drivers will be better placed to accommodate themselves to the lighting level of the tunnel. Overall, this technology will have a fair to positive effect on user safety and comfort. As the majority of tunnel accidents occur in the transition area of a tunnel (first 50 m), this proposed approach could reduce injury accidents. Improvements in the visibility of tunnel features and moving objects would also be achieved. A potential negative effect could be the increase of speeding, as drivers would feel more comfortable within the tunnel. Nevertheless, a positive improvement on the perceived subjective safety of tunnel users would be attained.

LED lighting with 'closed-loop' feedback, was assessed as having an overall neutral effect on user safety and comfort. The effects of this solution would have no direct impact on the user, as the correct lighting levels would be provided throughout the tunnel.

Tunnel monitoring systems were assessed as having a neutral to fair impact on user safety and comfort. The integration of various systems into a single management and monitoring system could have a fair and positive impact by (a) reducing the number of fatalities and seriously injured, and (b) reducing incident detection time and, thereby, reducing injury severity. The impact on the other factors that were assessed was neutral, as many of the functions of tunnel monitoring systems would have no direct interaction with the user.

The high voltage distribution and incentivising energy efficiency were assessed as having a neutral effect on user safety and comfort, as neither interacts directly with tunnel users.

Table 3-8: Qualitative assessment results

Category	Performance indicators	Reducing threshold luminance	LED Lighting with 'closed loop' feedback	Tunnel monitoring systems	High voltage supply	Incentivising energy efficiency
User safety	Reduction of injury accidents	**++**	**0**	**0**	**0**	**0**
	Reduction of fatally and seriously injured	**+**	**0**	**+**	**0**	**0**
	Reducing of speeding	**-**	**0**	**+**	**0**	**0**
	Reducing of speed variation	**+**	**0**	**+**	**0**	**0**
	Reduction of incident detection time	**0**	**0**	**++**	**0**	**0**
User comfort	Influence on visibility of tunnel features	**+**	**0**	**0**	**0**	**0**
	Influence on driver distraction	**0**	**0**	**0**	**0**	**0**
	Influence on blending level	**+**	**0**	**0**	**0**	**0**
	Influence on visibility of moving objects	**+**	**0**	**0**	**0**	**0**
	Influence on air quality	**0**	**0**	**0**	**0**	**0**
	Influence on perceived subjective safety	**++**	**0**	**0**	**0**	**0**

The results of the assessment show that overall, the technologies identified in REETS would, in terms of safety and comfort, have a neutral effect on tunnel users.

Regarding technological readiness (TRL), all systems can be considered at TRL 9, as they have been implemented in one form or another at specific locations. An example is the installation of a partial structure at Kingsway tunnel in the UK, which reduced threshold luminance. All the solutions identified would be ready for implementation, perhaps via specialist suppliers.

4 Conclusions and next steps

This deliverable provides a description and assessment of the five technologies that have been identified as having potential to reduce energy consumption in road tunnels. The assessment was performed both quantitatively for whole life carbon and life cycle cost, and qualitatively for user safety and comfort and technological readiness. Relevant tunnel and energy data as well as expert assumptions were used for the assessment.

The quantitative assessment showed that all five shortlisted technologies could provide savings in energy over the service life of a tunnel, even after deductions had been made for capital carbon ‘outlay’ embodied in the technologies and their periodic replacement. The picture for life cycle cost was similar, except that integrated tunnel monitoring required a significant outlay and frequent replacement. Integrated tunnel monitoring was the only ‘multi-functional’ technology, in the sense that monitoring energy use was just one of its many applications; further tangible benefits will be realised from its other applications and can be offset against the overall capital outlay (many of which are safety-motivated). Perhaps, as would be expected, technologies aimed to improve the efficiency of energy supply realised the greatest benefits. However, technologies aimed at smaller portions of the total energy usage should not be discarded since they can deliver a good return with smaller capital outlay and shorter payback period.

The qualitative assessment revealed that overall the five technologies would have a neutral to fair effect on user safety and comfort. It is paramount that the levels of these two characteristics are, at least, maintained if the technologies are to be implemented.

The next step of the Project will be to reappraise each technology for its suitability for deployment in two tunnels. It will involve the following activities:

- A desk study to determine the feasibility of implementation in a UK tunnel and an Austrian tunnel.
- Determining the life cycle benefits for those two tunnels.
- Considering how and when the selected technologies can be deployed to achieve optimal benefits and the least disruption for tunnel users.
- Carrying out sensitivity analyses to determine how dependent the costs and benefits are on changes such as energy prices, the time value of money, traffic demand, and the evolution of vehicle characteristics.

The findings of the next steps detailed above will be reported in REETS Deliverables 3.1 and 3.2.

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Annex A: Technological profiles

These profiles summarise the findings and can be used as standalone documents.

REDUCING THRESHOLD LUMINANCE

The aim of this initiative is to reduce the required lighting level in the threshold zone which, in turn, determines subsequent lighting levels in other zones. The threshold area of a tunnel is the first zone within a tunnel and is equal in length to the stopping distance. In the first part of this zone, the required luminance must remain the same and is linked to the outside luminance, called the L_{20}. Therefore, the lower the L_{20} can be, the lower the luminance in the threshold area can be. The use of screens or taut structures at the tunnel portal is intended to provide the threshold lighting levels from natural light as opposed to artificial means. To achieve this the tunnel is effectively extended by the screens or taut structures.

Area of energy consumption:

Lighting

Reference situation:

No daylight dimming prior to the tunnel entrance. A full artificial lighting requirement in the threshold zone.

MODEL INPUTS	
Tunnel baseline	>500 meters, 2-bore, 2 lane
Pre-deployment energy consumption (lighting)	150,059 kWh /year (threshold zones)
Post-deployment energy consumption (lighting)	33,114 kWh /year (threshold zones)
Cost of deployment	Deployment costs would be part of tunnel building costs. c. €400k per entrance
Extent of current deployment (%)	c.10 % across Europe
Replacement rate (over 120 years asset lifetime)	0
Installation and replacement conditions	Fixed structure would be installed during tunnel build

ASSESSMENT RESULTS	
Energy saving potential	116,945 kWh /year
Life cycle cost saving	€893k
Whole life carbon saving	5,446 tCO_2e
Impact on driver safety	Fair - Positive
Impact on driver comfort	Neutral
Technological readiness	9 (ready for implementation)

LED LIGHTING WITH 'CLOSED LOOP' FEEDBACK

The common 'open' loop dimming / switching process for the boost lighting currently used in tunnels is controlled by a portal photometer sensor, which constantly records the varying L_{20} values from the SD (sight distance) throughout the daylight hours. The alternative 'closed-loop' feedback is to compare what the photometer 'sees' and is calling for, compared to what is actually being delivered by the installed lighting. This is termed 'close-control'. The closed-loop, close-control would ensure that the correct level of lighting within the tunnel is being delivered in a dynamic method according to actual parameters therefore not over or in fact under lighting the tunnel.

Area of energy consumption:

Lighting

Reference situation:

LED lighting with conventional photometer sensors recording L20 values and adjusting boost lighting levels in threshold, transition and exit zones.

MODEL INPUTS	
Tunnel baseline	>500 meters, 2-bore, 2 lane
Pre-deployment energy consumption (lighting)	158,059 kWh /year (threshold zones)
Post-deployment energy consumption (lighting)	136,893 kWh /year (threshold zones)
Cost of deployment	c. €35k per entrance (would be wholly or partly offset by avoided requirement to replacement current light sensing systems)
Extent of current deployment (%)	c.15 % (mainly Austria and Germany)
Replacement rate (over 120 years asset lifetime)	Life cycle estimated at maximum 26 years
Installation and replacement conditions	Minimal – assumed to be deployed within current maintenance regime for LED lighting and sensors

ASSESSMENT RESULTS	
Energy saving potential	13,166 kWh /year
Life cycle cost saving	€95k
Whole life carbon saving	681 tCO_2e
Impact on driver safety	Neutral
Impact on driver comfort	Neutral
Technological readiness	9 (ready for implementation via specialist suppliers)

TUNNEL MONITORING SYSTEMS

Systems are available for monitoring the environmental conditions within a tunnel; such as air quality, lighting, sump levels, and incidents. These systems can improve the level of safety and optimize the day-to-day operation and maintenance of a tunnel. Through exploitation of the data produced, tunnels can be operated more efficiently and thereby lower energy consumption. Monitoring systems can detect early performance degradation, and thereby reduce the risk and consequences of unexpected and/or undetected failures of systems and components that could compromise the safe operation of the tunnel.

Area of energy consumption:

Overall operational demand

Reference situation:

Separate systems for tunnel monitoring

MODEL INPUTS	
Tunnel baseline	>500 meters, 2-bore, 2 lane
Pre-deployment energy consumption (overall)	1,095,000 kWh / year
Post-deployment energy consumption (overall)	1,040,250 kWh / year
Cost of deployment	c. €500k per bore
Extent of current deployment (%)	c.20 %
Replacement rate (over 120 years asset lifetime)	Life cycle estimated at maximum 12 years (system) and 26 years (cabling)
Installation and replacement conditions	Minimal impact - achievable within current scheduled maintenance regimes

ASSESSMENT RESULTS	
Energy saving potential	54,750 kWh / year
Life cycle cost saving	No saving (potential benefits beyond energy savings not evaluated)
Whole life carbon saving	2,831 tCO_2e
Impact on driver safety	Fair to Positive
Impact on driver comfort	Neutral
Technological readiness	9 (ready for implementation via specialist suppliers)

HIGH VOLTAGE DISTRIBUTION WITH VOLTAGE OPTIMIZATION AND DYNAMIC UPS AND AVOIDING DYNAMIC OSCILLATION

The use of high voltage distribution systems incorporating voltage optimization will result in the potential for energy and carbon savings.

The use of efficient UPS systems will enable the tunnel safety systems to operate in the event of a major power failure and also provide a limited amount of tunnel lighting.

Super-low loss amorphous transformers significantly reduce the losses experienced in both load and non-load states which provide savings on electricity consumption and lower carbon emissions.

Area of energy consumption:

Energy supply

Reference situation:

1. Based on combined transformer and voltage optimization, the reference situation is:
   - Electricity supplied at fixed voltage output from secondary side of transformer voltage
2. Based on existing transformer and Low Voltage (LV) side only voltage optimization using variable output to cater for primary side fluctuations, the reference situation is:
   - Low voltage side dynamic voltage optimization

MODEL INPUTS	Combined transformer and voltage optimization	Existing transformer LV side only voltage optimization using variable output
Tunnel baseline	>500 meters, 2-bore, 2 lane	
Pre-deployment energy consumption (overall)	1,095,000 kWh / year	1,095,000 kWh / year
Post-deployment energy consumption (overall)	930,750 kWh / year	974,550 kWh / year
Cost of deployment	c. €135k per bore	c. €93k per bore
Extent of current deployment (%)	0	0
Replacement rate (over 120 years asset lifetime)	Life cycle estimated at maximum 20 years	Life cycle estimated at maximum 20 years
Installation and replacement conditions	Minimal impact	Minimal impact

ASSESSMENT RESULTS		
Energy saving potential	164,250 kWh / year	120,450 kWh / year
Life cycle cost saving	€745k	€618k
Whole life carbon saving	8,434 tCO_2e	6,199 tCO_2e
Impact on driver safety	Neutral	
Impact on driver comfort	Neutral	
Technological readiness	9 (ready for implementation via specialist suppliers)	

INCENTIVISING ENERGY EFFICIENCY

Through procurement policy and contractual conditions, NRAs can incentivise the efficient use of energy in assets operated by contractors. A stepwise approach to lower overall energy use is often desired. Such an approach can be promoted by encouraging suppliers to avoid unnecessary energy use and/or switch to more energy efficient technologies by offering financial incentives and/or through the tender assessment process. In this case high efficiency motors are used for ventilation fans, as an alternative to the lowest efficiency motors that are permitted. IE3 motors replace IE1 motors.

Area of energy consumption:

Ventilation

Reference situation:

No financial incentives to achieve energy efficiency in procurement. IE1 motors used.

MODEL INPUTS	
Tunnel baseline	>500 meters, 2-bore, 2 lane
Pre-deployment energy consumption (ventilation)	175,200 kWh / year
Post-deployment energy consumption (ventilation)	168,542 kWh / year
Cost of deployment	IE3 motors estimated to be €270 more per unit
Extent of current deployment (%)	unknown
Replacement rate (over 120 years asset lifetime)	18 years (identical for lower and higher efficiency motors)
Installation and replacement conditions	Minimal impact

ASSESSMENT RESULTS	
Energy saving potential	6,658 kWh / year
Life cycle cost saving	€78k
Whole life carbon saving	344 tCO_2e
Impact on driver safety	Neutral
Impact on driver comfort	Neutral
Technological readiness	9 (ready for implementation via specialist suppliers)