WORKING TOWARDS A ZERO-ENERGY TUNNEL

Version 0.9 for the ITA in Bergen, Norway

ABSTRACT:. Road tunnels require large amounts of energy due to a comprehensive package of safety devices and the accumulation of various functions. In the coming years, new tunnels will be built and some existing tunnels renovated on a large scale. This provides opportunities for new developments in the fields of technical, contractual and process solutions. A reduction of over 50% in total energy consumption can be achieved by focusing on the four key aspects during the entire tunnel construction process.

The primary focus of this paper is on the results of an energy-reduction project related to road tunnels. It can be concluded that with the smart combination of the current technical, contractual and process measure-ments described in this paper, an energy reduction of around 50% can be obtained. In addition, all these measures satisfy the national legislation and the tunnel guidelines (LTS). This can be seen as a positive start in creating a zero-energy tunnel and infra-structure.

INTRODUCTION

The Dutch Ministry of Infrastructure and Environment, Rijkswaterstaat (RWS), is taking on a major challenge in order to achieve its policy objectives: *20% energy reduction in 2020 compared to 2010* (European Commission, 2010*) and a complete zero-energy infra-structure (RWS-2016/15377/155837).*

Road tunnels require large amounts of energy due to a comprehensive package of safety devices and the accumulation of various functions (Bloembergen, 2014) (Geesink, 2015). In the coming years, new tunnels will be built and a lot of existing tunnels will be renovated on a large scale. This provides opportunities for new developments in the fields of technical, contractual and process solutions.

In order to achieve these objectives, several expert teams have been created for the Energy Reduction in Tunnels Project with compositions based on their members' experience and skills. The project (COB, 2015) has resulted in a manual that stresses four key aspects:

- process measures;
- contracts;
- technical measures;
- combining key aspects.

The first aspect involves properly setting up the entire tunnel planning and construction process, and how the energy-reduction ambition fits herein.

The second aspect is the contractual incorporation of energy reduction, so that solutions are generated to negate adverse incentives and instead generate positive ones. In addition, suggestions are formulated concerning how measures can thrive in the different stages of the project—from the initial exploration phase up to and after the completion of the project.

The third aspect describes the technical measures in order to reduce the energy consumption of the tunnel subsystems. The last aspect involves combining the different mea-sures above so as to reach the highest energy-reduction potential.

The complete 'manual' is available as a living document on a wiki-style website (https://www.cob.nl/groeiboek/), which can be updated as needed. For the project, such a living document is ideally suited, as developments, particularly in the area of sustainability and technology, are continuously updated.

1. PROCESSES MEASURES

The process measures are the actions to be taken in the process of building, renovating or maintaining a tunnel in order to properly implement the technical and contractual measures. The effectiveness of the technical and contractual measures are determined by the process measures.

a. Start in the earliest project phases

It is important to be aware of the energy-reduction goal in the earliest project phases. The limitations imposed on the project during the initial planning and architectural design and the administrative consultation are not focused enough on energy reduction. Especially for new-build tunnels, the combination of a civil design adapted to technical energy reduction methods can lead to a tunnel design in which both elements can reach their full potential. In the case of existing tunnels, the policy objective can be achieved by smart combinations of the different technical measurements.

b. Reference design energy consumption

In order to properly assess the actions taken by the Contractors during an EMAT-Best Value Procurement (BVP) bid, a 'reference design energy consumption' has to be arranged and after the realisation of the design, this reference design is also needed to assess whether the proposed energy reduction is actually achieved.

In the case of existing tunnels, the energy consumption is known or can be calculated based on available subsystems. If some of the subsystems need to be renovated, the energy reduction per installation can be measured separately. In the case of new-build tunnels, the setup of a reference design energy reduction takes more time and is based on the features of the tunnel (e.g. the length, amount of tubes, geographical orientation and level of subsystem facilities etc.). In addition, the dynamic features (e.g. the amount of traffic, chance of traffic jams, amount of accidents etc.) of the tunnel are also significant.

It is important that, in this reference design, energy consumption is calculated in cases of both normal operation and during a calamity, because a considerable number of the subsystems will only activate in a calamity. The energy consumption of the different subsystems are explained in more detail in paragraph 3.

On the basis of the reference design energy consumption and the technical energy reduction methods, the tunnel owner can decide on the prescription of a technical measure. If the Client chooses to prescribe a technical measure, a realistic saving must be estimated and this should be incorporated in the reference design. Based on this revision, a tender panel can determine what the remaining potential energy saving needs to be and the objective and the weighting for the EMAT-BPK bid are determined based on this.

If the Client/tender panel created a reference design for energy consumption it can also be provided in the tender to the candidates/bidders. This reference design can be used by them to calculate the theoretical energy consumption based on their design as a time period can be chosen regarding the operating and/or maintenance period (e.g., fifteen years).

c. Cost-benefit analysis

To determine whether a measure will be carried out or not is, in most cases, based on a cost-benefit analysis. In many cases the economic savings are weighed against the costs. Unfortunately, this leads to several technical measurements with such a long payback period that they are not selected during a tender.

At this moment (spring 2017), the price of energy is low. Over a longer period, energy prices may rise again, which could induce a situation in which the investment could become profitable.

There are also measures that are economically viable in the long term. An example of this is the application of a daylight screen to reduce a pronounced share of the artificial lighting at the entrance zone of a tunnel, reducing both energy and maintenance costs. Unfortunately, the investment costs are high, making the return period longer than twenty years. However, the energy-reduction share is around 20%. Based on current insights regarding energy prices, a light screen is a positive measure in a political sense but less so in economic terms.

The cost-benefit analysis can be improved by taking the energy consumption and political objectives into account. When considering a technical measure, the measure should not be weighed against the energy costs, but against the quantity of energy consumption; the number of kWh which can be saved and not solely the cost of these kWh. An EMAT-BVP can contribute to this and should therefore contain sufficient incentives.

Next to economic considerations, Clients also have political and administrative goals. Nowadays society is focused on long-term sustainability and also tunnels need to contribute to that goal. Clients can therefore consider setting technical measures as a requirement based on political objectives and not due to pure economic reasons.

The latter two extensions of the cost-benefit analysis, which take energy reduction into account, make this analysis more complex. To facilitate this analysis, each technical energy reduction method contains two numbers: the first indicates the economic considerations and the second indicates the contribution to the energy-reduction objective (Table 1). The numbers are normalized to a scale of 1 to 5, where 1 characterizes a low (negative) score 5 and a high (highly favorable).

2. CONTRACTUAL MEASURES

The contractual measures are the incentives in contracts that have a positive effect on the application of the technical energy-reduction methods. There are three key factors for the implementation of energy reduction in tunnels:

- positive incentives in tender/contract;
- negative incentives in tender/contract;
- relation contract type and incentives.

a. Positive incentives in tender/contract

In this paragraph, eleven incentives are described which can be used within a contract by Clients.

'Make performance targets instead of effort commitments'

At the moment, contracts are based on effort commitments, often in the form of input requirements and are not based on performance (concrete results). To ensure that the desired level is reached, the required energy level must be defined within the contract. If the Contractor fails to comply with these requirements, a fine can be imposed and, in the worst case, the contract is terminated. This incentive is applicable to all contract forms, such as maintenance contracts and integrated contracts.

'Reservation reduction methods'

A reservation could be incorporated for the reduction measures that are implemented after the award. The costs are equal for both the Client as the Contractor and any profits will be distributed evenly.

'One-time payment for reduction methods'

A one-time payment to neutralize the invest-ment costs of energy-reduction methods after the tendering competition will lead to a lower risk profile for the Contractor. Therefore, the choice of investment costs for different reduction methods is not influenced by the financier.

'Implement a financial component into the contract'

In a DBFM contract, the payment takes places at the moment the project is available/ready to use. This payment system results in a project which is completed on time and which satisfies the project's quality and requirements. This can benefit energy reduction by setting the required amount of energy reduction as a goal and when the pre-set reduction percentage is not met, the

Table 1. Values used for the extension of the cost-benefit analysis: the first column indicates the economic considerations and the second column indicates the contribution to the energy-reduction objective

Value	Economically viable (Client perspective)	Contribution energy reduction objective
1	The measure has a very unfavorable cost-benefit analysis. The payback period exceeds 15 years.	The measure contributes hardly to the objective.
2	The measure has an unfavorable cost-benefit analysis. Additional incentives should be used to get this measure implemented.	The measure has only a limited contribution to the objective.
3	The measure has a favorable cost-benefit analysis but it requires a contractor who wants to distinguish themselves from the others (e.g. by means of a EMAT-BKPV).	The measure is worth considering.
4	The measure has a favorable cost-benefit analysis. It is most likely that a contract that stimulates energy reduction will contain this measure.	The measure contributes to the objective.
5	The measure has a very favorable cost-benefit analysis. The payback period is less than 3 years.	The measure contributes significantly to the objective (can be seen as a must-have).

contractor needs to bring the reduction percentage to the required level.

'Discount/fines for energy consumption'
This incentive is most beneficial when the energy consumption lies within the scope of contracts such as DBM or DBFM. When the reduction percentage is not as stated in the contract, the Contractor will receive a fine.

'The Contractor pays energy bills during and after construction'
The inclusion of such a contractual obligation is only possible if both management and maintenance is included within one single contract. This incentive has a positive influence on the energy consumption because the result of high energy costs lies with the Contractor. Contracts as DBM (Design, Build and Maintenance) and DBFM (Design, Build, Finance and Maintenance) lend themselves well to this.

'High (fictive) value for energy reduction'
It is important that the Client prepares and formulates the EMAT criterion in such a way that there is sufficient space for offering solutions that promote energy reduction. In order to stimulate the tenderers even more, the energy reduction item can be assigned a higher (notional) value than the other awarded criteria. In this way, tenderers will try to include competitive energy reduction measures in their offer.

'Functional specification'
Functional specification has the advantage of providing space for a Contractor to bring in their own expertise and creativity. Functional requirements can, employed in conjunction, influence the design of the Contractor but the design freedom and choices remain with the Contractor.

'Measurement of energy consumption subsystems as a requirement'
Setting the measurement of the subsystems' energy consumption as a management requirement has the advantage that, prior to upcoming renovations, a concrete energy reduction can be implemented in the contract.

'Energy reduction as an award criteria'
Energy reduction as an award criterion would not only be limited to quantitative calculations (eg DuboCalc) but should also provide space for the qualitative implementation of the EMAT-Best Value Procurement. The latter promotes the ability to make innovations. A qualitative assessment of this innovation would be sufficient for the evaluation of the actions (of the plan). The measures offered are then converted to requirements in the contract. Compliance is secured in this manner.

Table 2. Positive and negative incentives per contract type.

Contract types	
Traditional Contract	
Positive incentive	Client can prescribe energy reductions methods within the contract.
Negative incentive	The Contractor is not stimulated to use energy reduction methods when they are not stated in the contract.
Design and Construct (D&C)	
Positive incentive	Use of functional specification instead and don't set detailed requirements.
Negative incentive	No economic benefits when the Contractor takes the whole construction process into account.
Design, Build, Maintenance (DBM)	
Positive incentive	Take the whole construction process into account when setting the requirements for energy reduction.
Negative incentive	If the duration of the maintenance phase is not optimal so, that some energy reduction methods are excluded.
Design, Build, Finance, Maintenance (DBM)	
Positive incentive	A financial incentive for the Contractor to meet the requirements. Single payment to the Contractor in order to 'cover' for the investment costs.
Negative incentive	The reduction methods can affect availability and reliability.

'Different price/quality ratio'
A typical value distribution is 60% value and 40% quality. Making quality more central than price could be considered so as to apply an alternative ratio for quality, or to work with a fixed price and 100% quality.

b. Negative incentives in tender/contract
Contract types in which the maintenance phase is not included such as 'Design and Construct (D&C)' have a negative influence on the energy-reduction scope. In this situation, the Contractor does not take the long-term costs of the investment into account. In integrated contracts, which include the maintenance phase, the payment of the energy bills is a contractual obligation of the Contractor.

Another negative incentive is a limited financial component in the contract type. If there is less financing in the project, the financier has less interest in monitoring the quality which is supplied by the Contractor because he or she has less to lose. The Contractor may at some point, if too much is paid for the progress, lose his or her interest in the project and decide to quit, especially when he or she must address un-expected setbacks.

c. Relation between contract types and incentives
There is a connection between the contract type and the appropriate incentives. Some positive incentives do not work on certain contracts, while others are highly suitable. This also applies to negative incentives.

In construction practices concerning both new and renovation projects, a distinction can be made between traditional and integrated contracts. In a traditional contract, a separate contract is made for each phase and the responsibility for the interface lies with the Client.

In an integrated contract, various phases of the construction process are incorporated into one contract with one Contractor. In addition, an alliance contract is used occasionally in the infrastructure. In an alliance, different partners work together and share opportunities and risks with each other in highly complex and/or innovative projects.

In table 2, per contract type both the negative and positive incentives are described that influence the energy-reduction objective.

3. TECHNICAL MEASUREMENTS

The share of power consumption during normal tunnel operation can be divided into the following subsystems (estimates):

- 50% lighting system
- 22% energy subsystem & emergency power supplies
- 17% ventilation
- 11% building service

In addition to the main energy consumers, other technical aspects like pumps, pipes and the civil design also need to be reviewed in order to come to an optimal power consumption for the tunnel.

No energy meters are currently present on the various subsystems which measure the energy consumption per subsystem and these are mostly not required for a new project. To obtain insight into energy consumption, it is beneficial to place energy meters on the various subsystems both in existing and new-build tunnels. Monitoring voltage quality is also advantageous.

For each energy-reduction method, the difference between the installed power of a system and the actual energy consumption needs to be reviewed. For example, the ventilation subsystem has a significant installed capacity but is only active for a limited time and the lighting subsystem has a medium installed capacity but is continually active. This means that energy-saving measures are more effective for lighting systems than for ventilation systems.

The methods are focused only on a reduction of total energy consumption and are not based on sustainable generation techniques. The reduction methods are described according to the following pattern:

- A general description of the method.
- What are the energy efficiency advantages? The indication of the potential savings is based on a reference project or expert judgment. It should be noted that the actual saving will differ per tunnel.
- The compliance of the measure with the Dutch law (Warvw, Rarvw) and the National Tunnel Guideline (LTS).
- What are the consequences of this measure regarding availability/ reliability/ maintainability?
- What are the safety consequences?
- What are the consequences for the road user?
- Technology readiness level (TRL): an indication of the readiness of the technology behind the measure. The TRL is indicated by a scale from 1 to 10, where 1 indicates that the technique is still in a development phase and 10 indicates that the technique is standard and can be readily applied in tunnels (Table 3).
- What are the costs and benefits? An estimate of the costs and benefits, weighed in a classification from 1 to 5 (1 is unfavorable, 5 highly favorable). A distinction is made between the economic component and the contribution to energy reduction, as described in the previous chapter.
- References to websites and projects where the measures and/or techniques are described.
- Applicability in rail tunnels.

In the subsequent paragraphs, the different energy-reduction methods are discussed per subsystem. Per method the energy efficiency, technology readiness level (TRL) and the components of the cost-benefit analysis are shown in table 3.

3.1 Lighting system

The lightening system of a tunnel is essential for sufficient vision inside of a tunnel (avoiding black-hole effect). In addition, when driving into a tunnel, there should be sufficient visual information regarding the geometry of the portion of the road forming the field of view as well as the presence and movement of possible obstacles (the latter comprising other road users in particular) (CIE, 2004).

The design of lighting systems for daytime conditions is more complicated than for nighttime conditions, due to the high luminance outside the tunnel, which requires both a high luminance inside the tunnel and a smooth adaptation from bright to dark environments. The latter results in the fact that the lighting system of the entrance zone has the largest share of around 50% of the lightening system.

The different energy-reduction methods are based on the reduction of the (extra) required entrance lighting and the possibilities of LED technology such as dynamic control etc.

a. Daylight screens

The use of daylight screens ensures a smooth adaptation at the tunnel entrance. This system requires neither energy nor control circuits. There are different kinds of screens: pergola constructions and roof openings. Daylight screens are currently hardly used in the Netherlands for various reasons. The main reason is that it is easier to create contrary light by means of artificial light than by daylight. Unfortunately replacing the entire entrance lighting by daylight screens is not possible.

Depending on the tunnel location and construction, the daylight screens can be part of the tunnel ceiling, walls, or both. The use of daylight screens resulted in major energy savings up to a maximum of 80% (20% of total energy).

b. LED-technology

The use of LED technology for new-build tunnels is not new anymore, but most of the existing tunnels in the Netherlands are equipped
with high-pressure sodium lamps (HPS). The implementation of LED systems contributes to the optimisation of lighting systems (NSVTT, 2016) (Dzhusupova, 2012) as they are easily dimmable while maintaining a high efficiency according to the outside brightness, weather conditions, and traffic density with no partial maintenance during system life span. The use of LED technology leads to an energy reduction of 10% of the total tunnel energy consumption (in comparison to HPS).

c. Dynamic LED-technology

When the LED technology also consists of a dynamic control an even greater optimization can be reached. The reduction of the total energy consumption is 2.5-5%.

d. Reduction luminance level

At the moment, the required luminance levels in the entrance zone, according to the guidelines, are not based on the current LED system. It is supposed that the brighter light color of LED gives room for optimizing the luminance level. Reducing the required luminance level has a direct relationship with the energy consumption of the lighting. In the Netherlands a study will be performed in 2017 to investigate the possibilities. The possible reduction in the total energy consumption is 10-15%.

e. PV-cells

The luminance level of the entrance zone has a direct relation to exterior brightness—the higher the outside brightness, the higher the required luminance level. A link between entrance lighting and solar panels (PV) systems on site therefore seems obvious. In the grounds around the tunnel, sufficient space is available for placing the panels. A combination with the daylight screens (a) gives additional possibilities.

In view of the large amount of energy that is required in case of calamities is it is unlikely to generate all of the energy with PV systems. Placing the panels should be seen as an additional measure: the durable generation of the required energy consumption which remains after the implementation of the energy-reduction measures.

f. Light tubes

The function of a daylight tube is similar to that of a daylight screen, with the difference that the sunlight is captured, transported, and emitted into the tunnel interior. The system does not require either energy or control circuits. The reduction in the total energy consumption is less than 3%. Unfortunately, the efficiency is relatively low due to the great amount of surface area required to generate sufficient light. The technique can also easily be applied in service buildings.

In modern architecture, light pipes have been widely used to illuminate rooms with few windows providing natural light (Al-Marwaee and Carter, 2006a, 2006b; Carter, 2002). Nevertheless, light pipes have not been used to date in tunnel construction.

g. light walls

Bright walls result in a higher reflection value

Table 3. Values per reduction method for the technology readiness level and the cost benefit analysis.

Reduction methods	TRL value	Economic component	Energy reduction efficiency
1.Lighting system			
Day-light screens	10	1-2	5
LED-technology	10	4	5
Dynamic LED-technology	9/10	4	3
Reduction luminance level	10	4	4
PV-cells	10	4	3
Light tubes	7	2	1
Light walls	10	2	4
Reflexing white asphalt	6	3	3
Lighting system MTK	10	4	3
2. Ventilation system			
No separate overpressure system	9	5	2
Fans with a higher supply voltage	10	4	1
Use of more efficient fans	8	2	2
Smarter switch on process	10	3	3
Optimization ventilation system	10	3	3
3. Service buildings			
Direct-cooling system cabinets	9	2	2
Use of residual heat	6	3	1
Use of presence detection	10	1	1
Zero-energy buildings	6	-	4
4. Energy systems			
Optimization emergency power supplies	6	5	3
Improve power quality	8	-	1-2
Use of DC-network	6	-	-
Monitoring energy consumption	10	5	2

Technology Readiness Level
TRL 6: It has already been used in objects, but not in tunnels. In other words, the basic technique is known and can be developed in such a way that it is also applicable in tunnels.
TRL 7: The technique is widely used in properties, but not yet in tunnels.
TLR 8: The technique is used in tunnels in Europe and is known in the tunnel sector, but not yet implemented in the Netherlands.
TLR 9: The technique is used in non-empire tunnels in the Netherlands. The technique is fairly standard and can be applied with a small adaptation in more tunnels.
TLR10: Used in empire tunnels in the Netherlands. The technique is in such a way standard that it can be readily applied in the tunnels.

due to the use of lighter materials. This means that with less light, a higher contrast is perceived. A more efficient lightening system in the tunnel gives an energy reduction of 2-5% on the lightening component compared to the situation without light walls.

h. *Reflexing white asphalt*

This method has the same function as the previous one but in this case, white material for the road surface is used. When reflexing white asphalt is used, the required luminance amount can be decreased and an energy reduction of 12.5% can be reached for the lightening component.

i. *Lighting system (MTK)*

In a tunnel between the tunnel tubes often a central tunnel channel (MTK) is present, which provide a safe escape route in case of a calamity.
At the moment the lightening system (TL-system) in the MTK is turned on the entire time.
When also for the MTK a LED-system is used this could lead to an energy reduction of 2,5% for the total energy consumption of the tunnel.

3.2 Ventilation systems

The ventilation systems ensures the safety of the road users during normal operation and during a calamity. The capacity of the ventilation system cannot be decreased and so all possible reduction methods are based on the management and maintenance of the system.

Another major energy consumer is the overpressure system for the escape routes tunnels. The better these are made 'leakproof', the less air is required to keep the escape routes at overpressure.

a. No separate overpressure system

By the correct arrangement of the ventilation system in the other tube during an emergency operation, the connection shafts between the tubes can be kept free of smoke so that the overpressure system is redundant in its entirety. This leads to an energy reduction of 1% of the total energy consumption of the tunnel.

b. Fans with a higher supply voltage

The energy saving is marginal. The loss in the chain is thus equal, and fans are not significantly more effective at higher supply voltages.

c. Use of more efficient fans

Almost all fans are jet fans and there are currently new developments available based on the use of different materials and better modelling. These systems have not been extensively tested, but, based on expert judgment, a saving of 7.5% of the energy consumption of the ventilation system can be realised.

d. Smarter activation process

In practice, the ventilation systems are activated too often, unnecessarily, and in combination with too much power. The ventilation system is not only used in emergencies, but also for assuring air quality. In addition, the quality and degree of maintenance of sensors may also limit the number of claims. The use of a smarter activation process leads to an energy saving of 16% for the ventilation system.

e. Optimization ventilation system

Ventilation systems are initially designed according to their required use in emergencies. In practice, these are often fans with a heavy capacity. These fans are also used to maintain the air quality in the tunnel. The capacity required for this is significantly lower than the capacity of the installed fans. This means that it is interesting to set up a more optimised ventilation concept, which is also based on normal operation. This could lead to an energy saving of 2.5% (total tunnel).

3.3 Service buildings

Each tunnel has service buildings in which local operation systems, service facilities and technical areas for the necessary equipment are located. This section presents measures to reduce the power consumption of these buildings.

a. Direct-cooling system cabinets

With direct-cooling, the heat is cooled and mechanically ventilated at the source. This prevents the heat interfering with the air in the room and resulting in heat nuisance. This may directly be done with the outside air or air/water heat exchangers in the cabinets. Thus, the need for space cooling is reduced and/or space cooling becomes redundant. This could lead to an energy reduction of 3-5% of the total energy consumption of the tunnel.

b. Use of residual heat

Many systems in the technical building run continuously and produce heat. This heat is now dissipated, but could also be used for heating of the technical buildings and spaces in a tunnel.This could lead to an energy reduction of 2-4% of the total energy consumption of the tunnel.

c. Use of presence detection

In order to ensure that the lighting and heating/ cooling is not unnecessarily activated inside the building, there is the possibility of placing presence detection and/or set a sweep pulse. Presence detection is useful in often unmanned space. Regarding the total energy consumption of the tunnel, this could lead to an energy reduction of 0.5-1.5% (light), 2-3.5% (heat) and 4-6% (cooling).

d. Zero-energy buildings

As a general aim, it is possible to make the technical building energy-neutral. This can be achieved through a combination of efficient insulation, use of residual heat etc. In addition, from 2019 onwards, it is required that government buildings be nearly zero-energy. This could lead to an energy reduction of 11% of the total energy consumption of the tunnel.

3.4 Energy systems

The energy system in a tunnel is the part that provides the necessary energy for the consumers. When the main power is lost, the emergency power supplies take over this task. This paragraph describes measures to reduce energy consumption generally and that of emergency power facilities in particular

a. Optimisation emergency power supplies

Many of the uninterruptible power supplies (UPSs) currently employed exhibit low efficiency. The required capacity (power and connected to realise stand-by time of ap-proximately one hour) is relatively large and must be maintained by constantly charging the battery by the UPS. Optimising the emergency power supply will contribute only a few percent to energy reduction.

A greater saving can be obtained when the energy supply of the tunnel is optimised as a whole. Significantly more can be gained by reducing the required emergency power.

b. Improve power quality

Requirements allowing the monitoring of power quality aspects, including its true measurement, can prevent the unnecessary consumption of energy. Poor power quality is characterised by the presence of high harmonic flows and blind, asymmetry and an unnecessarily high voltage.

These issues cause pollution and/or unnecessarily high consumption in the internal electrical infrastructure which results in malfunctions, damage to the equipment and a shorter lifetime. This could lead to an energy reduction of less than 1% of the total energy consumption of the tunnel.

c. Use of a DC-network

Information and Communication Technology (ICT) systems and LED lighting systems in tunnels require a DC power supply. This justifies the use of a specific DC network in addition to a conventional AC network for the high net-worth consumers. Using a DC network in the tunnel leads to substantial savings in energy consumption and the use of alternative energy is easier.

d. Monitoring energy consumption

In current tunnels, energy consumption is often only measured at the main supply. These meters can already provide a lot of information on daily consumption but provide no insight into what amount of energy goes to which installation. A better understanding of the energy consumption is not only useful for administrators, but can also lead to savings in data analysis. Understanding energy consumption over the long term can also help in troubleshooting and predicting failure.

Applying monitoring leads to no energy reduction, yet it must be emphasised that information becomes available in order to develop initiatives for energy efficiency.

4. SMART COMBINATION

This last key aspect available to achieve energy reductions is that which requires the most from both the Client and Contractor.

To satisfy policy objectives, varying methods need to be combined—not only for methods of the same subsystem, but also regarding methods for other subsystems. The combined effect of the different measures needs to be determined judiciously, as these measures influence each other. In table 4, an example is presented of a combination of technical measures wherein a reduction of more than 50% is possible.

It is up to suppliers to take up the challenge and build a solid foundation for an energy consumption that is not just as efficient and effective as possible, but also becomes more energy efficient throughout its life cycle.

5. FUTURE SCENARIO

The Centrum Ondergronds Bouwen (COB) presented a long-term vision on tunnels since, in past years, the emphasis was placed on the availability, safety and reliability of tunnels. The new tunnel law, the National Standard Tunnel and the professionalization of both Clients and Contractors ensure that we are now in a transition phase and it is time to look beyond the problems of today.

The large number of tunnels that need to be renovated in combination with the sustainability challenge, technical develop-ments and continual high availability and reliability requirements demand a reformulated vision on tunnels. Although the creation process is not yet completed, it is already clear that adaptability will be the key message of the vision.

An adaptive tunnel works towards a zero-energy tunnel. Developments in the field of smart mobility and the transition from fossil fuels to renewable energy will play a major role in the feasibility of the zero-energy tunnel. The energy transition offers great opportunities to add additional features and local energy generation/storage to tunnels. There are also great opportunities in the framework of the objectives in the circular economy field. By designing modular tunnels and developing innovative forms of ownership and use, it is possible to stimulate suppliers and manufacturers to maximize durability. In addition, the adaptive tunnel will also work towards integrated energy solutions.

We have to work towards an adaptive tunnel that can adapt relatively easily to future developments and requirements, including in the field of energy. This adaptability applies not only to the materials used for the physical tunnel and its accompanying installations, but also includes the multifunctional use of the tunnel and its adaptability over time (day/night or seasonal cycles), depending on the user's needs. All these aspects have potential implications for space and energy consumption.

Towards a zero-energy tunnel: 5 roads to discuss

With the energy reduction catalogue, made in the Netherlands we claim to be able to develop en renovate tunnels with a 50% energy reduction. **But how should we move towards a zero-energy tunnel? We have five main roads we would like to discuss, develop and walk with an international network.**

1. Adaptive and smart lighting

The lighting system determines to a large extent the energy consumption of a tunnel. This means that reduction of energy consumption through lighting directly results in a big profit.

Therefore, the first line of research is aimed at reducing these energy consumers.

Short term (2017-2020)

- We want to do research on all the aspects of **adaptive lighting**. It is necessary to look beyond pure technology, because we have insufficient knowledge in the field of experience, psychology and the functioning of the eye. Which luminance level is required in order to make sufficient contrast in case of new lighting concepts. Can we gain insight into the psychological aspects of tunnel visibility? Is there a difference in the desired luminance level in day and night situation? What are the conditions for adaptive lighting and what is the definition of adaptivity in a modularly constructed tunnel system? What can be the reflective function of wall and floor in tunnels?
- We create a high level of energy reduction with the **reintroduction of light-screens** at the entrance and exit of tunnels, but this strutural solution requires smart solutions that can quickly be integrated into existing constructions and design, smart use of other civil structures in the surrounding, easy to maintain, good to combine with local power generation and don't affect the safety -and availability level of the tunnel.
- We start this year with the **placement of solar panels** on tunnels and service buildings in the Netherlands for local power generation.

Long term (2020-2030)

- In which way can new lighting systems, as already developed for social security, contribute to road safety of tunnels from the perspective of the user?
- How can we introduce self-luminous light concepts by using big data, which permanently reduces energy consumption in combination with predictable and minimal maintenance?
- What luminance level is required for autonomous cars to drive safely through a tunnel?

2. From AC to DC-Network

Current electronics works largely on DC (direct current). In addition, most of the renewable energy sources also supply DC. In tunnels, we see that, next to the large amount of electronics, the lighting systems also operates on a DC network. This calls for an examination of the current energy network based on alternating current, AC.
We see added values and oppurtunities for using DC-networks. This does not only lead to a

reduction in the transformation losses but the equipment within the tunnel will also be smarter and with less components. In addition, 'non-durable' components such as batteries and transformers will no longer be needed. Unfortunately, today's electronic systems and interfaces are not ready yet for this implementation.

Short term (2017-2020)
• What are the preconditions (both technical and non-technical) that a DC network should meet to be suitable for use in tunnels?
• What are the preconditions (both technical and non-technical) that need to be imposed on systems and interfaces to make them suitable for use in a DC network in tunnels?
• Which systems and interfaces are best suitable for use in tunnels?

Long term (2020-2030)
• To be decided later

3. The smart tunnel as part of a smart grid

Sustainable local power generation and energy storage have gained momentum and offer opportunities for the development of smart tunnels. How can the tunnel become part of a smart grid and what conditions should local power generation and power storage meet to accommodate these vulnerable infra-objects? What is actually the definition of a smart, adaptive tunnel if we desire in the future a zero energy tunnel? Are self-learning systems a solution for the large energy consumers such as fans in the tunnel? How can we simplify traffic management and speed reduction systems?

Short term (2017-2020)

- Setting the agenda for the tunnel aspects in already developed / to be developed tracks around smart grids, such as the Amsterdam Sustainable Initiative and the implementation of the Environmental Act (role of decentralized authorities).
- Formulate prerequisites for integrating tunnels into a (already existing or new-to-build) smart grid.
- What conditions should local power generation and storage fulfil to make them suitable for use in tunnels?
- Can the next generation of photonics sensor technology be a partial solution towards the zero energy tunnel?

Long term (2020-2030)

- What opportunities does a tunnel provide for energy generation and storage?
- In case of a downgrade of the tunnel, for example if smart mobility lowers down the safety requirements, how can we turn off those large energy consumers or create new concepts that combine features?
- Can hydrogen act as a source regarding to durability and safety?

4. Lifecycle asset management and energy reduction

Asset management of infrastructural works is still in its infancy and tunnels are no exception. Although this topic is wider than energy reduction, it is important to take also asset management into account. Therefore, the most important design shift is that tunnel usage is a key factor in design choices. When this shift is applied, it is important to take energy reduction during all stages of tunnel construction into account. As stated in the long-term vision of tunnels, energy reduction is mainly about adaptivity. Adaptivity is an opportunity to work from a tunnel that costs energy, towards a tunnel that generates energy.

Short term (2017-2020)

- Incorporating the theme of energy reduction in our range of measures in such a way that also the construction and demolition phase are taken into account.
- How do we ensure that functionality, security, availability and sustainability are brought in balance with standards, policies and laws?
- Can we implement the use of CO2-neutral concrete in tunnel construction projects as part of sustainable purchasing?

Long term (2020-2030)
• How does the changing function and traffic influence the energy consumption of a tunnel? What other functions beside the networkfunction can be found in a tunnel? (watertransport / storage)?
• What should be done to transform the tunnel into a self-learning system by using big data?

5. Playing together in a safe environment

To make a vulnerable object like a tunnel adaptable, we need to work together on a **virtual playing field** in which we can practice, test, verify and finally validate. Developments in the field of big data make this kind of playing field much easier.

In this environment we can, first at concept level and later at a detail level, explore what the potential profit is and what the issues are which we need to take into account.

Short term (2017-2020)

- Can we stimulate the creation of a virtual playing field from the ambition of a zero-energy tunnel?
- Can we use that virtual play field to get a grip on the human factors? By for example using augmented reality, for insight into the actual visibility and safety of tunnels?
- Can we look at our virtual playing field to renovation projects on network or national level and looking for value creation instead of simply recovering what's up?

Long term (2020-2030)
• How can the playing field be adapted so that we are able to work with non-experts on spatial and security issues?
• How can our contract forms reflect the developing character of this task?

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Table 4a. Energy reduction per aspect based on a smart combination of several reduction methods.

Smart Combination			
Lighting system			
Reduction method	Reduction percentage lighting system entrance zone	Reduction percentage basic lighting system	Reduction percentage total lighting system
Daylight screen	80 %	-	40%
Reduction luminance level	25%	25%	25%
Light walls	-	3%	2%
Reflexing white asphalt	-	25%	13%
Total	*	*	**65%***
Ventilation system			
Reduction method	Reduction percentage per aspect		
Use of more efficient fans	7,5%		
Smarter Switch on process	16%		
Optimization ventilation system	2,5%		
Total	**26%**		
Service buildings			
Reduction method	Reduction percentage per aspect		
Zero energy building	**100%**		
Total	**100%**		
Other			
Reduction method	Reduction percentage per aspect		
based on expert judgement	15%		
Total	**15%**		
**The reduction percentage is calculated as 100% - (0.20 x 0.75) = 85%.*			

Table 4b. Total reduction in energy consumption by converting the energy reduction per aspect to the reduction percentage on tunnel level.

Aspect	**Percentage total energy consumption**	**Reduction percentage per aspect**	**Reduction percentage total energy consumption**
	[%]	**[%]**	**[%]**
Lighting system	50	65 (70)	33 (35)
Ventilation system	17	26	4
Service buildings	11	100	11
Other	22	15	3
Total	**100**		**51 (53)**
(*) The values in brackets show the reduction in energy consumption in case of combining the daylight screens with PV-cells.			