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Working Towards a Zero Energy Tunnel: Technical, Contractual and Process Solutions

The Dutch Ministry of Infrastructure and Environment, Rijkswaterstaat (RWS), is taking on a major challenge in order to achieve its policy objective: 20 % energy reduction in 2020 compared to 2010. This means that the energy demand of existing and new tunnels must be reduced by 48 %. In order to achieve this objective, different expert teams have been created for the project Energy Reduction in Tunnels with compositions that are based on their members' experience and skills. It has been concluded that with the smart combination of the current technical, contractual and process measures 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 infrastructure, for which The Netherlands Knowledge Center for Underground Space and Underground Construction (COB) will seek international coalitions.

Die Vision eines „Null-Energie-Tunnels": Technische und vertragliche Aspekte, Prozessoptimierungen

Das niederländische Ministerium für Infrastruktur und Umwelt, Rijkswaterstaat (RWS), stellt sich einer großen Herausforderung, um sein politisches Ziel zu erreichen: 20 % Energieeinsparung im Jahr 2020 im Vergleich zum Energieverbrauch im Jahr 2010. Dies bedeutet, dass der Energiebedarf von bestehenden und neuen Tunneln um 48 % reduziert werden muss. Um dieses Ziel zu erreichen, wurden verschiedene Expertenteams für das Projekt Energieeinsparung in Tunneln gebildet. Die Zusammenstellung der Teams basiert auf den Erfahrungen und Fähigkeiten der Mitglieder. Es wurde der Schluss gezogen, dass mit der geschickten Kombination der in diesem Papier beschriebenen aktuellen technischen, vertraglichen und verfahrenstechnischen Maßnahmen eine Energieeinsparung von ca. 50 % erzielt werden kann. Darüber hinaus entsprechen alle diese Maßnahmen den nationalen Rechtsvorschriften und den Tunnelrichtlinien (LTS). Dies kann als positiver Start für die Schaffung eines Null-Energie-Tunnels und einer Infrastruktur gewertet werden, für die das Netherlands Knowledge Center for Underground Space and Underground Construction (COB) internationale Zusammenarbeit anstreben wird.

1 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 [4] and a complete zero energy infrastructure [8].

Road tunnels require large amounts of energy due to a comprehensive package of safety devices and the accumulation of various functions [1], [5]. 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 project Energy Reduction in Tunnels with compositions based on their members' experience and skills. The project [2] has resulted in a manual that stresses four key aspects:

- Process measures,
- Contract measures,
- Technical measures,
- Combining key aspects.

The first aspect involves properly setting up the entire tunnel planning and construction process, and fitting the energy-reduction ambition therein. 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 measures above so as to reach the highest energy-reduction potential. The complete 'manual' is available as a living document on a wiki-style website, which will be updated continuously, particularly in the area of sustainability, technology, and the way projects make the manual work [9].

2 Process 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 is determined by the process measures.

2.1 Start in the earliest project phases

It is important to be aware of the energy-reduction goal in the earliest project phases. To date, the limitations imposed on the project during the initial planning and architectural design and the administrative consultation are mostly not focused enough on energy reduction. Especially for new 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 a smart combination of the different technical measures.

2.2 Reference design energy consumption

In order to properly assess the actions taken by the contractors during an economically most advantageous tender (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 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, number 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, number 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 is explained in more detail in the next paragraph.

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 the desired remaining potential energy saving 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 the bidders to calculate the theoretical energy consumption of their own design. A time period can be chosen regarding the operating and/or maintenance period (e.g. fifteen years).

2.3 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 measures 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.

Value	Economically viable (client perspective)	Contribution to 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).

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.

Next to economic considerations, clients also have political and administrative goals. Nowadays society is focused on long-term sustainability and tunnels need to contribute to that goal, too. 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 and 5 a high (highly favorable).

2.4 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.

Positive incentives in tender/contract

- Make performance targets instead of effort commitments,
- Reservation for reduction methods,
- One-time payment for reduction methods,
- Implement a financial component into the contract,
- Discount/fines for energy consumption,
- The contractor pays energy bills during and after construction,
- High (fictive) value for energy reduction,
- Functional specification,
- Measurement of energy consumption subsystems as a requirement,
- Energy reduction as an award criteria,
- Different price/quality ratio.

Negative incentives in tender/contract

- Contract types in which the maintenance phase is not included such as 'Design and Construct (D&C)',
- A limited financial component in the contract type.

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 influences the energy reduction objective.

3 Technical measures

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 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 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

Contract types	
	Traditional Contract
Positive incentive	Client can prescribe energy reduction 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

Table 2 Positive and negative incentives per contract type

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 Dutch law (Warvw, Rarvw) and the National Tunnel Guideline (LTS) [7].
- 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. A scale from 1 to 10 indicates the TRL, 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 unfavourable, 5 highly favourable). 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 lighting 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 informa-

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.

Table 3 Values per reduction method for the technology readiness level and the cost benefit analysis tion 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) [3], [6].

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 lighting 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, which are:

- Daylight screens,
- LED-technology,
- Dynamic LED-technology,
- Reduction luminance level,
- PV-cells,
- Light tubes,
- Light walls,
- Reflexing white asphalt,
- Lighting system (MTK).

3.2 Ventilation systems

The ventilation systems ensure 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. The following reduction methods are proposed:

- No separate overpressure system,
- Fans with a higher supply voltage,
- Use of more efficient fans,
- Smarter activation process,
- Optimization ventilation system.

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, which are:

- Direct-cooling system cabinets,
- Use of residual heat,
- Use of presence detection,
- Zero energy buildings.

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 presents measures to reduce energy consumption generally and that of emergency power facilities in particular, which are:

- Optimisation emergency power supplies,
- Improve power quality,
- Use of a DC-network,
- Monitoring energy consumption.

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

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.			

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

3.5 Smart combination

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

4 Future scenario

The Netherlands Knowledge Centre for Underground Space and Construction (COB) presented a long-term vision on tunnels since, in past years, the emphasis was only placed on the availability, safety and reliability of tunnels. The new tunnel law, the National Tunnel Standard 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 developments and continual high availability and reliability requirements demand a reformulated vision on tunnels. Adaptability is the key message of the vision and the roadmaps for research that follow this 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.

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