Zero energy Tunnel-concept

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8/29/2012

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A catalogue record is available from the Eindhoven University of Technology Library

ISBN: 978-90-444-1145-4
(Eindverslagen Stan Ackermans Instituut ; 2012/043)

Summary

Creating a zero energy environment is a hot topic. The developments in this field are based on the concept of the “Trias Energetica”: reducing energy consumption, using renewable energy sources, and efficient using of fossil fuels. Zero energy concept can be also applied to road tunnels to improve the energy performance by means of reducing energy consumption, introducing of renewable energy generation and thus lowering energy bills.

Zero energy tunnel concept is a good approach to make the road tunnel more energy sustainable and environmental friendly. The developments in this field are based on the next aspects:

- Sustainability
- Health
- Economic issues.

Road traffic in a tunnel is a source of an atmospheric pollution which has to be managed both inside the tunnel to protect users’ safety and well being and outside the tunnel in order to limit the environmental impact. In most of the tunnels in the Netherlands, there is a feedback system so that high concentrations of pollutants inside the tunnel trigger the ventilation to increase the visibility level. The visibility level has a strong relationship with the concentration of dust. These measurements are required by means of tunnel safety standards and not related to the human well being aspect. There are hardly any examples in the world where the contaminant removal technologies are applied in tunnels for external air quality purposes.

The goals of the Zero Energy Tunnel project study are:

- To find possible solutions to decrease energy consumption in the tunnel
- To investigate innovative solutions to make the tunnel environmental friendly
- To implement renewable energy generation and energy storage to make tunnel a zero energy element
- To establish the needed power flow between all the components and medium voltage grid with keeping power quality at an acceptable level
- To develop a Zero Energy Tunnel conceptual design.

In this study the contribution to the main goals is done by means of reducing energy consumption of tunnel lighting system; designing air cleaning systems; designing the heat extraction system that utilize the heat generated by tunnel traffic; and finally designing the renewable energy generation and energy storage to achieve the energy balance on yearly basis.

Management advice

Based on the study results reported in the current document the author can advise the followings:

- One of the solutions to reduce energy consumption in the tunnel is the implementation of LED lighting system. Thus, a significant energy consumption reduction for tunnel lighting can be achieved.

- There is a high possibility that the requirements from the government for air quality inside and outside the tunnel will be stricter in near future. To eliminate the possible future question for tunnel owners: i.e. how to meet these requirements, the author made a research in this field as well. There are two possibilities to improve the air quality in the tunnel: either increasing longitudinal ventilation system output or implementing air cleaning technologies. The impacts on total tunnel energy consumption of these two possibilities are almost equal. However, the environmental impact of tunnel pollutions can be eliminated by installing an air cleaning system.

- Most of the tunnels in the Netherlands have a chemical uninterruptable power supply (UPS or no-break system) such as batteries. However, chemical batteries require often replacement and maintenance. The proposed solution is to replace them with a flywheel UPS combined with back-up generator. Flywheel technology has much longer life-time (25-30 years) and does not require the same amount of maintenance.

- The installation of renewable energy sources such as wind turbines and solar panels together with electrical energy storage is a good way to cover the tunnel electrical energy demand. Apart from meeting the sustainability goals, it gives the additional possibility to the tunnel owners to get financial benefits from selling the electrical energy back to the grid.

- Finally, implementation of the heat extraction system in the tunnel is a good way to utilize the heat generated by tunnel traffic and gain some financial benefits meanwhile.

Acknowledgment

This report describes the study that has been performed in the framework of my project in the second year of PDEng traineeship in SAI-ICT, “Zero Energy Tunnel”. I would like to thank all the people who contributed to my research. The output of this research would not be the same without their help. I would like to thank the director of the SAI-ACT, Prof. Dr.-Ing. L.M.F. Kaufmann for giving me the opportunity to be in this program, and for guiding and supporting me during this two years. I would also like to thank the head of EES group, Prof.ir. W.L. Kling for finding me such an interesting topic for my final project. I am grateful to my daily supervisor, Prof.dr.ir. J.F.G. Cobben for his guidance and advices. I would also like to thank the director of KIEN, A. van Duijne, for his support and keeping me always motivated during the research. Also I am very thankful to them for giving me the opportunity to attend the DIgSILENT Power Factory seminar “Grid connection of Renewable Generation” in Gomaringen, Germany. Moreover, I would like to thank Ugur, my sisters Dina and Lilya, and my aunt Galja for their help during this year. Finally, I would like warmly thank my parents, who are away from me. I thank them for their support and belief in my ability to overcome all the obstacles in my life.

Contents

Chapter 1

1 Introduction

1.1 Background

Based on the data obtained from the list of tunnels located in the Netherlands, in a tunnel construction most of the energy is consumed by the lighting system. The estimated share of energy consumption for tunnel lighting is around 50%. Currently, there is a significant amount of energy wastage in the tunnel lighting due to its inability for fast light dimming according to real-time measurements.

Another important aspect is emission concentration inside and outside the tunnel. In the Netherlands the measurements of the emission concentration have a strong relationship with measurements of visibility level in the tunnel. In fact, the visibility in the tunnels is related to the concentration of dust. Nowadays there is no control of gas emissions in the tunnel. According to the interviewed people from Ministry of Transport, Public Works and Water Management (Rijkswaterstaat) the gas emission concentration in the tunnels and at the tunnel portals are below the limits. However, there is a difference between the current requirements for the emission concentration limits according to Dutch Ministry and Dutch Expert Committee on Occupational Standards DECOS (a committee of the Health Council of the Netherlands): i.e. 4 mg/m^3 and 0.5 mg/m^3 respectively [1]. At present, in the Netherlands there is no air cleaning system implemented in a tunnel construction. Usually, there is a feedback system so that high concentration of dust triggers the ventilation system to increase the visibility level inside the tunnel. These facts raise discussions about the well being of people living near to the tunnel portals. However, there is an exception from this common situation: Coentunnel, Amsterdam. In this particular tunnel design emission shafts are applied. By this way, the dirty air from the tunnel is pulled out via these shafts to be disperse into the atmosphere on 25 m height. This design requires additional ventilation, that affects significantly the total tunnel energy consumption: i.e. energy demand is more then 17 000 MWh per year, and the electrical energy bills are more than 1.5 million euro per year. The share of additional ventilation system energy consumption in this tunnel is about 40% of total tunnel demand [2]. Moreover it does not completely solve the problem of impact of the tunnel emission on air quality outside the tunnel portals. Thus, more proper solution has to be proposed.

1.1.1 Tunnel design

Based on data for the different tunnels located in the Netherlands provided by one of large tunnel contractors Croon and the Ministry of Transport, Public Works and Water Management (Rijkswaterstaat), it is possible to describe the tunnel systems and their energy consumption. In general, there are several systems:

- *Lighting.* Involves the tunnel lighting system

- *Drainage.* Drainage system includes water pumps which help to eliminate a permanent water leakage in the tunnel
- *Ventilation.* Currently used to improve the visibility level in case of heavy traffic and pull the smoke out of the tunnel during fire
- *Traffic installations.* Includes different types of signals and signs
- *Fires extinguish system.* Includes pumping system designed for fire situations
- *Communication installation.* Includes video surveillance system, phone communication, etc.
- *Building service system.* Mainly, this is a cooling system for operating rooms. Operating rooms are the rooms where high voltage equipment, transformers, back-up generators; and the data control center are located. Data control center are data control cabinets which collect and process all the data from the tunnel installations. The temperature in operating rooms is high due to the heat produced by mentioned above equipment. Thus, additional electrical energy is needed for the air cooling system.

During normal operation conditions the tunnel uses around 40% of the installed power. The biggest share of it has the ventilation system. Based on the investigation, it is 44% of the total installed power. The figure below shows the share of the installed power in a tunnel based on data from the different tunnels in the Netherlands [2],[3],[4],[5].

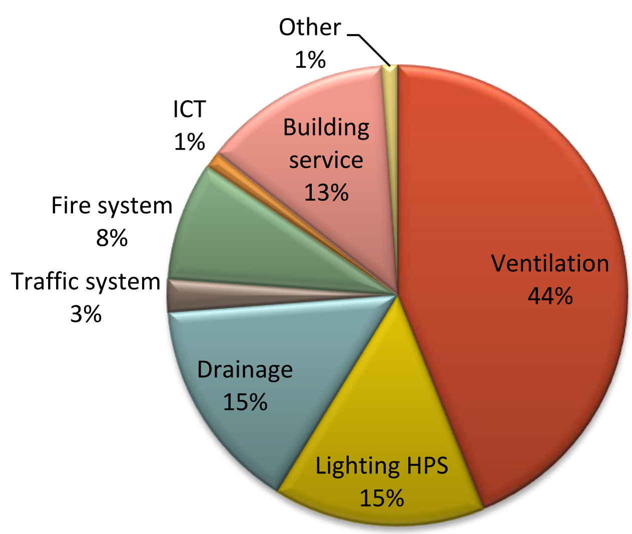

Figure 1 Share of installed power in the tunnel, % from total installed power [2],[3],[4],[5].

The share of energy consumption during normal operation significantly differs from the share of installed power. Figure 2 presents the share of energy consumption during the normal operating situation in the tunnel, and it is based on the research results. As it can be concluded from Figure 2, the energy share of lighting system is the biggest one. According to Leidraad Energiezuinig Ontwerpen [Rijkswaterstaat] the share of energy consumption for tunnel lighting is around 40% in a tunnel type A (average speed more than 100 km/h). The general opinion of tunnel experts gives the value of 50% and more. Due to the fact that calamity situations are very rare in the Netherlands, significant saving of energy can be achieved by reducing the energy consumption of the lighting system.

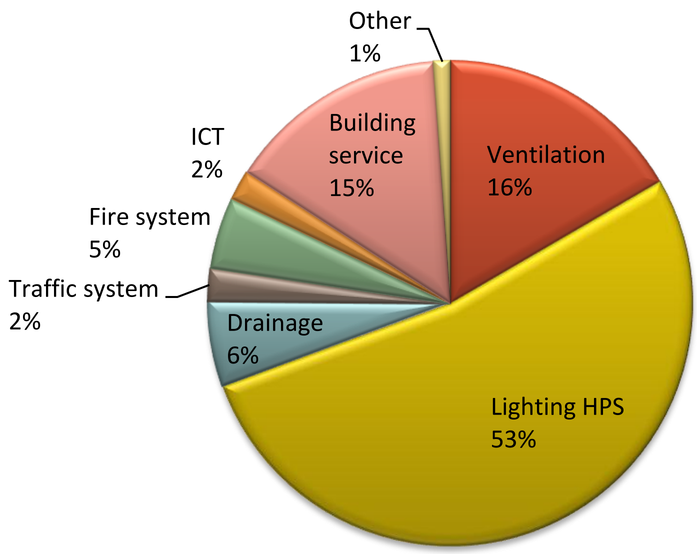

Figure 2 Share of energy consumption during normal operation conditions, %

The current study focuses on lighting and ventilation systems. However, in new tunnel concept the additional systems are developed and described in the next Chapter 2.

1.1.2 Zero Energy Tunnel project study goals

The goals of the Zero Energy Tunnel project study are:

- To find possible solutions to decrease energy consumption in the tunnel
- To investigate the innovative solutions to make tunnel environmental friendly
- To develop a renewable energy generation and an energy storage
- To establish the needed power flow between all the components and medium voltage grid with keeping power quality at an acceptable limit
- To develop a Zero Energy Tunnel conceptual design.

To achieve the goal of transforming a real tunnel into a zero energy tunnel, the project development should pass several milestones. These milestones are presented as a triangle in Figure 3. At the basement of the triangle there is an idea of the project, the next layer is the framework aspects. Each framework aspect has its system aspects. Finally, each system aspect needs to be designed. These layers refer to the developing of the Zero Energy Tunnel concept stage and are in the scope of the university research. The following detailed design and specification are developing the concept design. In this stage the tunnel contractors and governmental organizations should be involved. At the top of the triangle the implementation and operation stage, and, in case of successful finalizing the project, the final goal will be achieved.

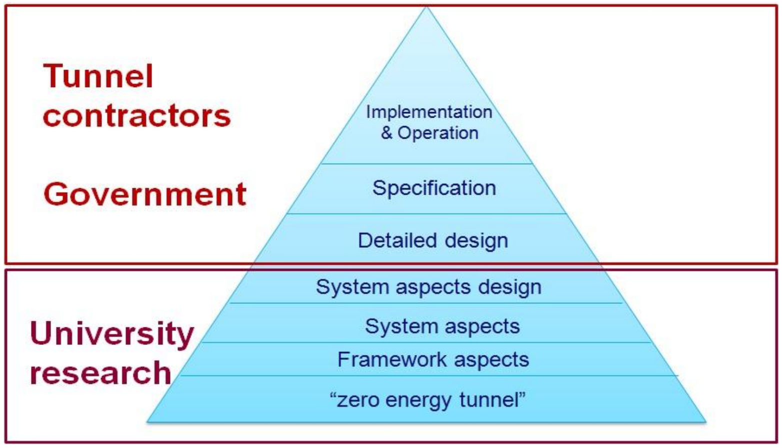

Figure 3 Zero Energy Tunnel project milestones

The framework aspects developed in zero energy tunnel concept are shown in Figure 4.

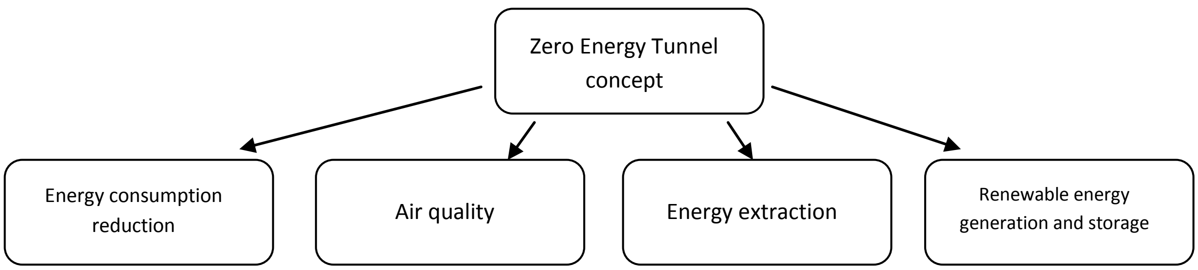

Figure 4 Developed framework aspects of Zero Energy Tunnel project

1.1.3 Boundary conditions for the project

In the Netherlands during the first 25 years, most of the tunnels are operated by tunnel contractors. After that period Rijkswaterstaat (Ministry of transport and Water Management) becomes the tunnel owner. However, all the requirements are issued and controlled by Rijkswaterstaat during the design and construction phases. Thus, the main factor as tunnel safety should be kept according to the requirements. The tunnel contractors are very interested in new innovative technologies which can help to reduce the cost of tunnel operation and improve the air quality. However, the restriction is that the payback period for the investments would be less than 25 years. That is the reason why only proven technologies are taken in the consideration in this study.

Maintenance aspect is a challenge for the "zero energy tunnel" concept. The system design involves the implementation of new technologies related to cleaning the air inside the tunnel and heat extraction from the tunnel. All additional installations can cause additional maintenance. However, during the detailed design, the maintenance of new installations can be matched with the current maintenance schedule. There is a risk for tunnel contractors to pay a penalty in case the pilot tunnel would not be successful. However, it is possible to involve different companies in the implementation stage and share the risk as well. These companies could be different tunnel contractors, local government, banks, etc.

1.1.4 Zero Energy Tunnel concept

Zero Energy Tunnel concept assumes that during the normal operation tunnel installations are connected with the grid. The own generated power can be used to cover the tunnel load or can be sold back to the grid. Electrical energy storage is used to store the energy generated from the renewable energy sources or purchased from the grid. The stored energy can be used during grid failure, or during normal operation conditions if it is more economical attractive. For example, when the price for electrical energy is cheap, it can be purchased and stored. When a purchase price for the electrical energy would increase, it can be used to cover the tunnel demand. Electrical energy storage can also be used to smooth the load behavior of the tunnel during calamity situations. Uninterruptable Power Supply (UPS) is coupled with the back-up generator. UPS is used for fast recovering of voltage and frequency in case of short interruption of the grid. In case the interruption is long, it gives time for back-up generator to start up. The back-up generator is used to keep the delivered power at an acceptable level during long disconnection from the grid. This generator can be combined with the energy storage or it can be a separate diesel generator.

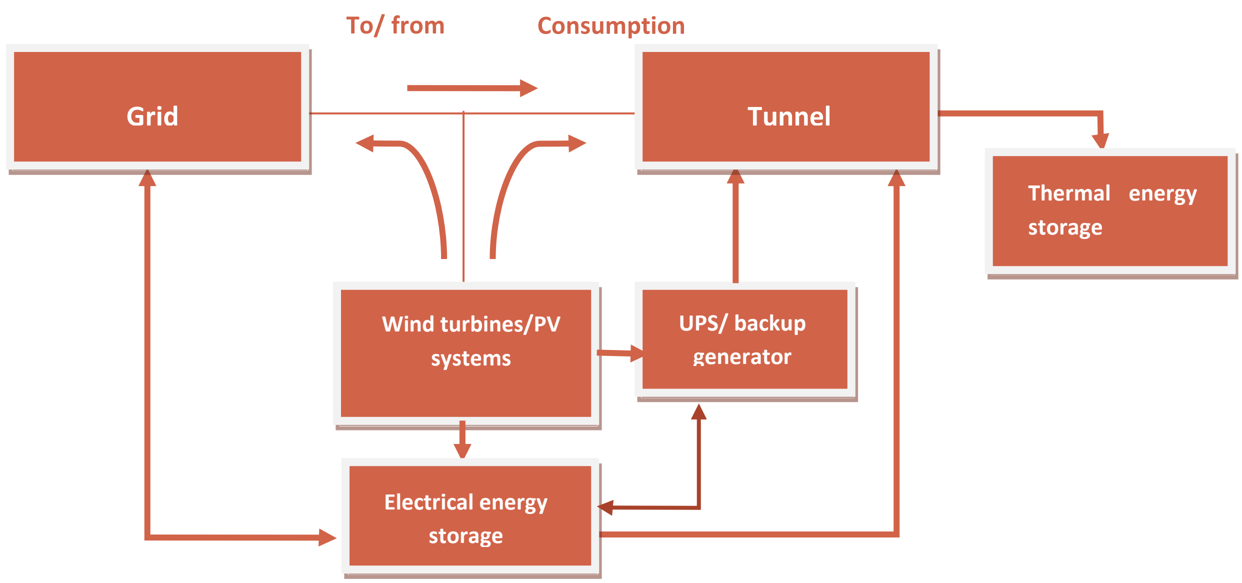

Figure 5 The schematic interpretation of Zero Energy Tunnel concept

1.2 Study objectives

The study is based on a ‘typical’ Dutch tunnel with a length of 1 km, and two tunnel tubes with a cross section of each tube of 75 m^2. The rush hours traffic flow through the tunnel tube is assumed to be 4700 vehicles per hour (based on an average traffic data of list of the tunnels located in the Netherlands). These data are taken as parameters for the model tunnel considered in this research. Thus, the model tunnel is a tunnel which has following systems: drainage, longitudinal ventilation, traffic installations, fires extinguish, communication, building service and lighting. It also has general characteristics of the highway tunnels in the Netherlands. Its parameters are described in Table 1.

Table 1 Model tunnel parameters

Length of tunnel tube, m	Tunnel tube area, m^2	Tunnel design	Speed, km/h	Traffic density in tunnel tube, vehicles/hour	Traffic flow
1000	75	2 tubes x 3 lanes	100	4700	unidirectional

The main objectives of the study are:
- To develop the framework aspects
- To define system aspects and their design. Within this stage the following systems are considered: tunnel lighting, ventilation, air cleaning and heat extraction
- To present the new model tunnel concept that includes the design of these systems and renewable energy sources. The study does not include the investigation of drainage, traffic installations, fires extinguish, communication and building service systems
- To prove the model tunnel concept by simulating the electric power flow and the total tunnel energy consumption/generation on yearly basis
- To introduce the possible options of environmental friendly electrical energy storage and uninterruptable power supply technologies and calculation their basic characteristics to match the model tunnel design requirements.

The study does not include:

- Financial estimation for implementation of the developed concept
- Maintenance of the designed tunnel systems. However, the investigation of the lifetime of several systems is presented in the report.
- Safety requirements for the Zero Energy Tunnel concept

To prove the model tunnel concept the DIgSILENT Power Factory software is chosen. DIgSILENT PowerFactory has standard power system analysis tools. The elements of electrical scheme are already developed in the software and their parameters can be adjusted easily. It is also possible to estimate the losses of electrical components. With help of this software it is possible to make a proper power quality analysis when all the parameters of each element of the scheme will be defined precisely in the concept detailed design.

This study is executed as the one year final project of the Professional Doctorate in Engineering (PDEng) in Information and Communication Technology, a two years Post-Master Designer Program that is offered by the Stan Ackermans Institute (SAI) at Eindhoven University of Technology (TU/e), part of the Department Electrical Engineering. The research is initiated and supported by KIEN. KIEN is an initiative of Stichting Elektrotechnische Ondernemers (SETO). It is supported by a broad mix of organizations: UNETO-VNI, electrical installers, Eindhoven University of Technology, research institutes and government. The goal of KIEN is to establish the link between innovative technologies and their practical application. It collaborates inside and outside the industry and develops project concepts for their implementation.

1.3 Study strategy

The initial phase of the study includes two steps:

- Investigation the current tunnel design. It includes the basic research of the tunnel construction in general, investigation the current energy consumption and the background of the tunnel requirements; interviewing the people from Ministry of Transport, Public Works and Water Management (Rijkswaterstaat) and tunnel contractors as well as visiting the tunnels that are under construction.
- Defining the common problems existing in the tunnels and investigation of possible ways to eliminate them. Defining the study framework and system aspects based on the investigation results.

The execution phase includes the systems design. The objectives of this phase are:

- Designing the tunnel lighting system to decrease energy consumption in the model tunnel
- Designing the air cleaning systems for model tunnel
- Designing the heat extraction system
- Choosing the renewable energy sources and their capacity as well as capacity of back-up generators for model tunnel scheme
- Investigation an electrical energy storage and uninterruptable power supply technologies based on the model tunnel demand and chosen capacity of the renewable energy sources.

In finalizing phase the simulation study is done. For this phase the following steps are performed:

- Developing the model tunnel scheme in DIgSILENT Power Factory software, using the results of the design stage
- Simulation of annual model tunnel consumption/ generation and performing the power flow analysis.

1.4 Report outline

The report is organized as follows. Chapter 1 introduces the concept of Zero Energy Tunnel. Chapter 2 includes the design of lighting, air cleaning and heat extraction systems; choosing the type of renewable energy generation sources and their capacity, and performing the payback period analysis; investigation of an electrical energy storage and uninterruptable power supply technologies appropriate for model tunnel. Chapter 3 describes the simulation study of annual energy consumption and generation; power flow analysis; and introduction of power quality in the new model tunnel. Finally, Chapter 4 provides the overall conclusions of the report and in Chapter 5 the future research is discussed. Appendix I presents the calculation of the number of jet fans and required fresh air flow according to the required concentration limits. Appendix II describes the wind turbine characteristics applied for the simulation study. Appendix III compares the uninterruptable power supply used nowadays and proposed for the new tunnel concept. Appendix IV presents the developed model tunnel scheme. Appendix V gives baseline document that have been written during Project Based Management course.

Chapter 2

2 System design aspects

Within the framework aspects, the system aspects and their design are defined. The considered aspects are: lighting system, air quality systems, electrical energy storage and uninterruptable power supply (no break), heat extraction system and renewable energy generation. The systems such lighting and ventilation exist in the nowadays tunnel design. However, the air cleaning and heat extraction systems are treated as innovative solutions to improve air quality in the tunnel, decrease environmental impact of tunnel emissions and gain benefits by utilizing the heat generated by the tunnel traffic. The obtained results from this chapter are the input for the model tunnel scheme and will affect on the capacity of renewable generation sources, electrical energy storage and uninterruptable power supply together with back-up generators.

2.1 Tunnel lighting system design

Based on the investigation results presented in Figure 2, the tunnel lighting system is considered as the biggest energy consumer. That is the reason to focus the research on the lighting system within the energy consumption reduction aspect. In this chapter the comparison of the energy consumption of model tunnel equipped with High Pressure Sodium (HPS) and with recently developed Light Emitting Diodes (LED) lighting is presented. The calculations are based on the designed lighting system for the model tunnel according to the requirements from International Commission on Illumination (CIE 88-2004) for tunnel lighting.

Nowadays, HPS lamps are mostly used as tunnel lighting. High pressure sodium lamps have many advantages such as longer lamp life, maximum efficiency, and small lamp size. However, it is a pointed light which causes a flicker effect and they have poor color rendering. In current tunnels equipped with HPS lighting system, the dimming of light during the night time is done by switching off the number of lamps, which increase the flickering effect in the tunnel. Another type of lamps which can be used for tunnel lighting is the fluorescent lamps. The fluorescent lighting was common used in the past, before developing the HPS tunnel lighting system. The benefits of this type of lamps are the quick start-up, and a line light design, which is preferable for tunnels. However, their large size makes them hard to maintain, and these lamps require special and expensive ballasts. Traditional fluorescent lamps have a low efficacy: i.e. more fluorescent lamps are required to provide the same light levels as other lamp sources. Furthermore, hard maintenance makes the exploiting of them expensive. Due to mentioned reasons this type of lamps are not considered in this study.

2.1.1 Lighting requirements

It is very important that objects on the carriageway should be visible at a sufficient distance: i.e. there must be adequate contrast between the object, the carriageway and the tunnel walls. Moreover, a high-speed traffic increases the importance of driver discretion and responses that are influenced by the eye adaptation process. To achieve these requirements, the design of tunnel lighting system must have following properties:

- The lighting should give the carriageway an adequate luminance level, and the luminance should be uniformly distributed over the carriageway
- The lighting design must not produce flicker effect
- Small cars following behind large lorries must be visible when the daylight at the exit is glaringly bright
- Lighting design should take into account the traffic speed.

The luminance level in the tunnel is based on the amount of time that the driver's eye needs to adapt to the change from the ambient light to the light at the tunnel entrance (or threshold) zone. Sufficient illumination must be provided to eliminate the "black hole" effect that obstructs the driver view at the access zone during daylight hours. Varying road surfaces and the speed of traffic affect the lighting levels. The quality and maintenance requirements are considered in this chapter as well. In practice, considering day time, tunnel is divided into five lighting zones. These zones are required by International Commission on Illumination (CIE 88-2004) for tunnel lighting.

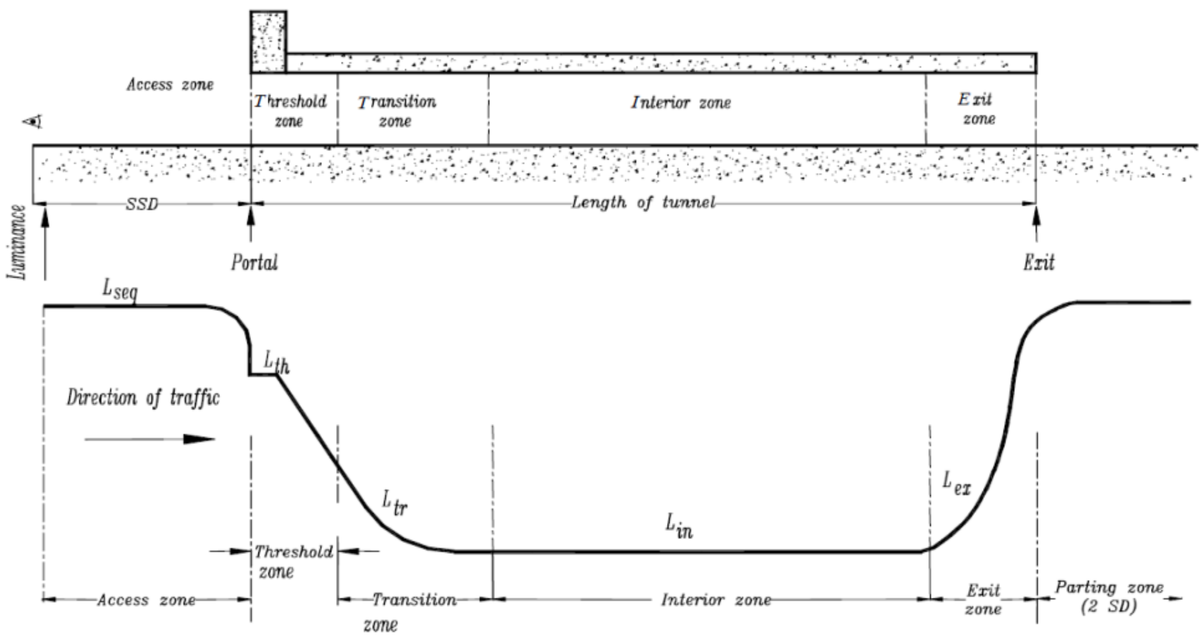

Figure 6 Tunnel lighting zones [6]

2.1.1.1 *Luminance evolution along the tunnel*

The access zone is not a part of the tunnel itself, but it is the approaching road just before the tunnel entrance. The length of the access zone is consequently equal to the safe stopping distance (SSD) and depends on the traffic speed. The maximum ambient light in this zone determines the luminance in the threshold zone at the beginning of the tunnel. The luminance level in access zone is determined on the basis of empirical correlations with speed and surroundings, and is not in the scope of this study. For presented calculation the luminance in the access zone (L_{20}) is taken as 6000 cd/m^2 [7].

The required luminance level in the first section of the threshold zone, which length is equal to the safe stopping distance, is related to the outside luminance level, L_{20}. In the transition zone the lighting level is gradually reduced towards the level as required in the interior zone. Visual adaptation from low to high level takes place instantaneously. However, the exit zone with gradually increasing lighting level is required for safety reason. It makes the following car visible in the rear-view mirror of a car leaving the tunnel. The lighting level evolution in Figure 7 is required by the latest tunnel lighting standard, CIE 88-2004.

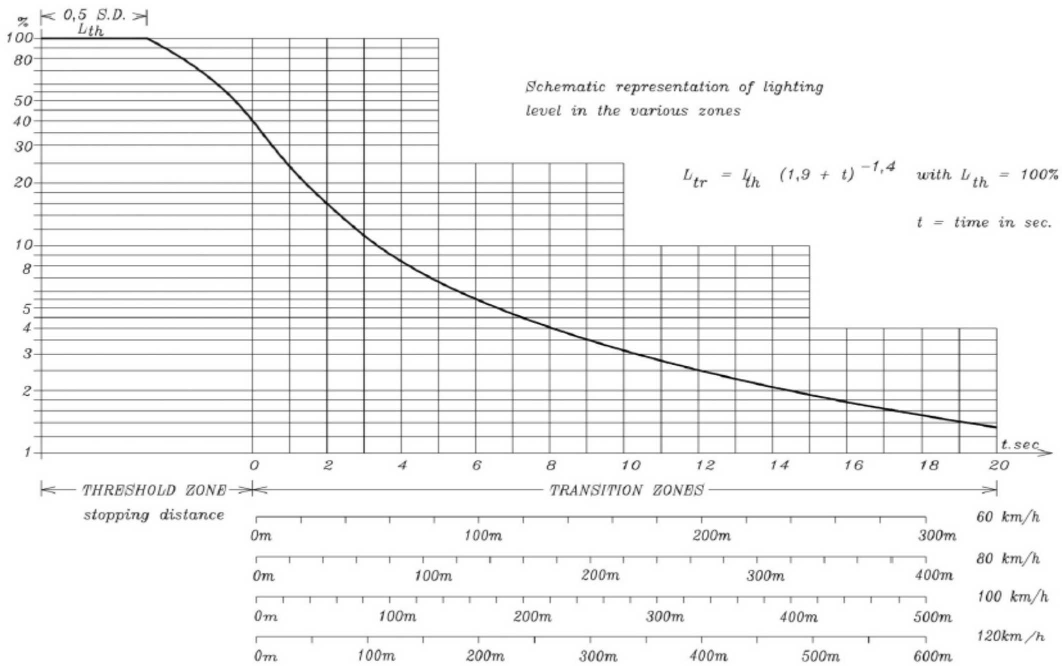

Figure 7 Required luminance evolution alongside the tunnel [6]

Luminance calculation of threshold zone is based on recommended threshold/access zone luminance ratio value, k=0.07.

Equation 1

$$L_{th} = L_{20} * k$$

The estimated luminance in each zone presented in Table 2 and based on traffic speed as 100 km/h in the tunnel.

Table 2 Estimated luminance in the tunnel zones

Zone	Length, m	L, cd/m^2
Access	120	6000
Threshold (1st and 2nd parts)	60	420
	60	266
Transition	500	39
Interior	260	6
Exit	120	213

2.1.2 Brightness

Brightness is an attribute of a visual perception and is used as a synonym for luminance. Human's eyes can only see light between 380 nm and 780 nm. The wavelength of HPS lamps is around 600 nm, and the length of LED is between 400 nm~700 nm. Hence, due to the light range of LED lamps is much more similar to the visible light, it seems brighter. According to the Dutch norm (NSVV) and [8] for LED lamps, it is possible to decrease the luminance approximately on 10% of the required level for each tunnel zone due to their high brightness.

2.1.3 Energy consumption estimation for different lighting systems

According to lighting specialists, a LED based system is an energy saving solution due to its ability to dim the light level. Other systems can also dim the light level up to some extent, but the efficiency of these systems is dramatically low compared to LED based lighting systems. For example, HPS systems can dim the light level up to approximately 50% with acceptable system efficiency. LED system can easily dim the light level within 0-100% with high efficiency without affecting the service life [9]. Furthermore, HPS lighting system consists of the pointed lamps that cause flicker effect (sequence of light and dark gaps) making the driving in the tunnel less comfortable and less safe for drivers. Thanks to the fast dimming ability of the LED lighting system, the tunnel lighting can be designed according to outside brightness, weather conditions, and traffic density. Thus, the energy consumption can be reduced significantly.

During the night time LED system can decrease light level on 90%. This is acceptable value according to the tunnel specialists. However, the minimum luminance level during night time must be not less than 2.5 cd/m^2 [10]. According to general weather conditions in the Netherland the following dimming schedule for lighting system can be assumed for all year round as:

Table 3 Assumption for LED system light output as a function of time

Time	Light level, %
6am - 8am	30
8am - 11am	60
11am - 3pm	90
3pm - 6pm	60
6pm - 6am	10

Table 4 Assumption of HPS system light output as a function of time

Time	Light level, %
8pm - 8am	30
8am – 8pm	100

Assumptions:

1. Tunnel has two tubes and three lanes in each tube. The width of each lane is around 5 m. Thus, the tunnel tube width is 15 m,
2. Tunnel tube height is 5 m,

3. Lambertian surface, where surface reflect isotropic luminance in every direction. In this case the luminance can be converted into electric power by the following equations [11]:

Equation 2

$$E = L * \pi$$

Equation 3

$$\Phi = E * A$$

Equation 4

$$P = \Phi/\eta$$

Equation 5

$$A = tunnel\ tube\ width * tunnel\ zone\ lenght$$

Where:

P = power, W
A = zone area, m^2
η = LED: 100 lm/W; HPS: 90 lm/W
E = illuminance, lm/m^2
Φ = luminous flux, lm
L = luminance, cd/m^2

Table 5 Luminous flux calculation in the tunnel tube

Zone	Length, m	L, cd/m2	Zone area, m^2	Illuminance, lm/m^2	Luminous flux, lm	Power, kW	
						LED	HPS
Threshold	60	420	900	1319	1186920	11	13
	60	266	900	836	752211	7	8
Transition	500	39	7500	123	921945	8	10
Interior	260	6	3900	20	77150	1	1
Exit	120	213	1800	669	1204724	11	13
Total	1000	945	15000	2967	4142949	37	46

Table 6 Energy consumption of lighting system in the tunnel

Lamp type	Power, kW	kWh per day	kWh per night	Total per tunnel, kWh	Total per year, MWh	Saving energy per year, MWh	Saving energy, %
HPS	92	1104.9	331.4	1436.2	524.2	279.2	53%
LED	75	581.7	89.5	671.2	245.0		

Thanks to the dimming ability and light spectrum of LED lamps, it is possible to reduce energy consumption for lighting system in the tunnel on 53%. The results obtained in DIgSILENT Power Factory software show that the total tunnel annual energy consumption reduction that can be reached by implementation LED lighting is 12%.

2.1.4 Maintenance

The LED system does not require the same level of maintenance during the life time period. HPS lamp units can become out of order during operation time, which is a disadvantage. In case 10% to 50% of the lamps become out of order on the length of 200 m, the tunnel owner must close the tunnel for an unplanned maintenance [12], which may cost a lot, e.g. for Coentunnel the fine is between 10,000 and 40,000 € per 15 min. A LED system designed for the tunnel consists of a large number of small LED lamps that creates line light. Even some of them would be out of order, it would not be noticeable by drivers. Due to LED system dims the light level during the day, it does not keep constant light output. This fact keeps their performance during the life time. According to LED system manufacture (INDAL) only the whole system can be replaced at once when the life time period is over [8]. It has additional positive influence on the payback period.

Table 7 Life-time and maintenance aspects comparison [2]

Lamp type	System lifetime	Maintenance
HTS	15 years	per 1.7 year
LED	15 years	per 15 years

2.1.5 Summary

The possible energy saving for the tunnel lighting system can be reached 53% by introducing LED instead of HPS lighting. This result is correlated with the real measurements in Vlaketunnel, The Netherlands, where the implementation of LED system reduces the tunnel lighting energy consumption by 50%. Based on the simulation results the total tunnel annual energy consumption can be reduced on 12%. An implementation of LED system as a tunnel lighting has some advantages and disadvantages:

Advantages:
- Easy dimming
- No partial maintenance during system life time
- No flickering effect
- line light (more safe).

Disadvantages:
- Investment cost.

To estimate the real value of the payback period, except the energy saving cost, the additional costs for LEDs, their maintenance and the installation should be considered. The big advantage of a LED system is that it does not need the partial maintenance [8]. This fact could reduce the payback period significantly. However, the installation cost may differ between HPS and LED systems. Moreover, LED system for a tunnel may have a line light, which eliminates the flickering effect and improves the safety in the tunnel.

There are other possibilities to decrease tunnel lighting energy consumption. Louvre and the real-time measurements of the amount and angle at which the sunlight enters the tunnel can reduce the L_{20}, and thus proportionally reduce the amount of light and energy needed in the tunnel zones. These options can be considered during the detailed design.

2.2 Tunnel ventilation in relation to the air quality

Based on the investigation, the common problem for tunnels in the Netherlands is the air quality inside and outside the tunnel. There is a high possibility that the requirements from the government for air quality would be stricter in near future and would include also gas emission control. Due to this fact the Zero Energy Tunnel concept focuses on the air quality aspect. There are two possibilities to improve air quality in the tunnel: either increasing longitudinal ventilation system output or implementing air cleaning system. In this section the comparison of longitudinal ventilation system energy consumption for two cases is presented: current situation and future situation when the requirements for the air quality would be stricter.

2.2.1 Requirements for tunnel ventilation system

The design and the control of the ventilation system have to meet the requirements such as:

- Smoke control requirements
- Air quality requirements.

There are three basic types of mechanical ventilation systems: longitudinal, transverse and semi-transverse. In the Netherlands, there is almost no use of transverse and semi-transverse systems. Due to many tunnels are located under water. Requirements from Ministry of Transport, Public Works and Water Management (Rijkswaterstaat) were set to use only longitudinal ventilation system. It was done to standardize the control for tunnels. Furthermore, only unidirectional traffic is allowed in each tube [13].

2.2.1.1 Smoke control requirements:

In the Netherlands the tunnel ventilation system design is based on the required air flow velocity in the safety standard. Usually ventilation system is designed for a maximum air flow velocity to be 8m/s inside the tunnel [14]. However, according to [15] the air flow velocity between 1 and 2.5 m/s is enough to provide safety in the tunnel. This air flow velocity is enough to prevent a back layering effect during fire and help to safety evacuation of the people. The relationship between minimum air flow velocity and fire intensity is shown in Figure 8. In Table 8 the fire intensity in relation with the size of vehicle is presented.

Table 8 Fire intensity caused by different vehicle type [14]

Vehicle	Thermal power
Personal car	2.5-8MW
Bus and truck	<100MW
Large truck	>100MW

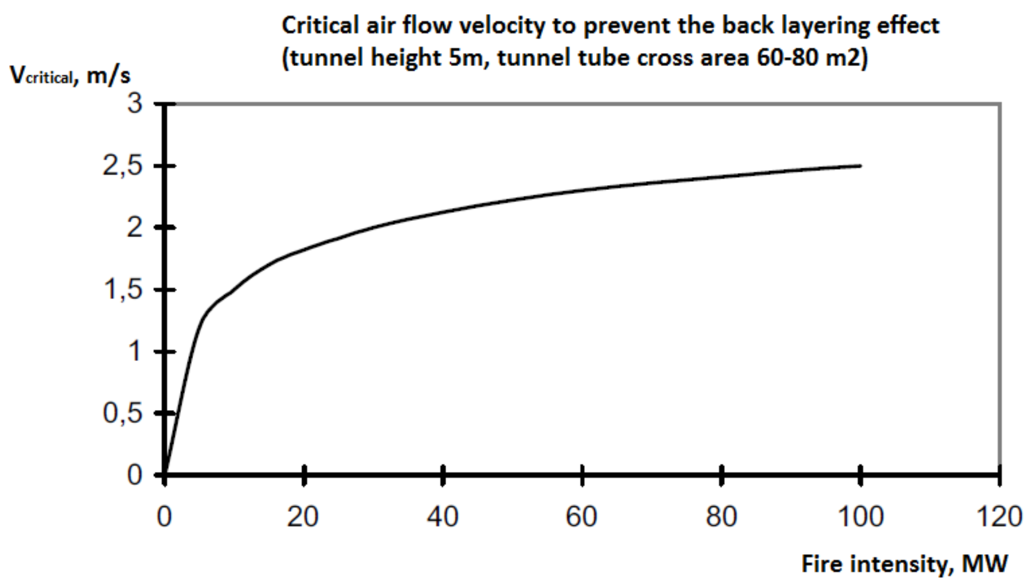

Figure 8 Critical air flow velocity in relation to the fire intensity [16]

Moreover, a high velocity of air flow influences the location of emission concentrations in the tunnel. The increase of air velocity would cause a high emission concentration in the lower region of the tunnel, which would be harmful to drivers [17]. According to the experience, in the Netherlands the probability of a big fire is very small. During the fire the main problem is that jet fans that are close to the fire source would be out of order. The standard for the jet fans thermal resistance in the Netherlands is 250°C for 1 hour [15]. An important extra degree of safety is achieved if the fans are suitable for 400°C instead of 250°C.

2.2.1.2 Air quality requirements

2.2.1.2.1 Tunnel emissions

Road traffic in the tunnel is a source of an atmospheric pollution that has to be reduced inside the tunnel to protect users' safety and well being of the people living near to the tunnel portals. In a tunnel, the emission concentrations can reach between five and ten times the concentrations of a normal road [18]. Based on the general opinion of different authorities the considered emissions in the tunnel are Carbon monoxide (CO), Nitrogen Oxides (NO_x) and Particulate matters (PM). Based on the investigation, the summary of admissible emission is presented in Table 9.

Where:

PIARC Permanent International Association of Road Congress
DECOS Dutch Expert Committee on Occupational Standards
AVV2005 Aanbevelingen Ventilatie van Verkeerstunnel
WHO World Health Organization

Conversion factor (20 °C, 101 kPa):
NO_2 1 mg/m^3= 0.52 ppm; 1 ppm = 1.91 mg/m^3
CO 1 mg/m^3= 0.871 ppm; 1 ppm = 1.148 mg/m^3

Table 9 Emission level according to different authorities [1], [19], [20],[21], [22]

		NO_2	$PM_{2.5}$	PM_{10}	CO
Ambient					
PIARC					5.74 mg/m^3 (5ppm)
DECOS		0.021 mg/m^3 (0.018 ppm)			
Maximum admissible level					
PIARC					80.36 mg/m^3 (70 ppm)
WHO	15 min				100 mg/m^3 (87.1 ppm)
	30 min				60 mg/m^3 (52.3 ppm)
	1 hour	200 µg/m^3 (0.11 ppm)			30 mg/m^3 (26.1 ppm)
	8 hours				10 mg/m^3 (8.7 ppm)
	annual mean	40 µg/m^3 (0.023 ppm)	0.01 mg/m^3	0.02mg/m^3	
	24h mean		0.025 mg/m^3	0.05mg/m^3	
AVV2005	1-2 min	1.88 mg/m^3 (0.978ppm)			
	2-5 min	1.1 mg/m^3 (0.572 ppm)			
	5-10 min	0.75 mg/m^3 (0.39 ppm)		5 mg/m^3	40mg/m^3 (34.84 ppm)
	1-8 hours	0.2 mg/m^3 (0.104 ppm)		5 mg/m^3	29 mg/m^3 (25.26 ppm)
DECOS	15 min	1.0 mg/m^3 (0.52 ppm)			
	8 hours	0.5 mg/m^3 (0.26 ppm)			
Ministry	8 hours	4 mg/m^3 (2.08 ppm)			

Carbon monoxide (CO)

There are many studies are going on about the negative influence of low CO concentration on human health. In case the tunnel is located in an urban area, the outside environment can be dangerous for inhabitants due to the continuous effect of low CO concentration. According to World Health Organization (WHO) the CO concentration level outside the tunnels must be much less than 8 ppm to keep people living close to the tunnel portals out of danger [19].

Nitrogen dioxide (NO_2)

NO_2 is part of NO_x emission (usually estimated as 10% to 20% of NO_x) caused by diesel engine exhaust. NO_2 is also an indicator for a cocktail of other pollutants emitted by road traffic that can cause health problems. The Dutch Expert Committee on Occupational Standards (DECOS) recommended for nitrogen dioxide of 0.5 mg/m^3 (8 hours) and of 1.0 mg/m^3 (15 min). However, due to socio-economic constraints, the Netherlands has set a legal occupational exposure limit of 4 mg/m^3 (8 hours) [1].

Particulate matter

Particulate matters (PM) are also known as fine particulars occur due to the combustion process in diesel engines. It is composed as a list of chemical elements, including sulphates, ammonium, nitrates, elemental carbon, condensed organic compounds, carcinogenic compounds and heavy metals such as arsenic, selenium, cadmium and zinc. Particulate matter comes in many sizes, from coarse particulates (less than 10 microns in diameter) to fine particulates (less than 2.5 microns), and to ultrafine particulates (less than 0.1 microns). Ultrafine particulates, which are small enough to penetrate the cells of the lungs, make up to 80-95% of diesel pollution [21]. The primary health concern caused by particulate matter is cardiovascular and respiratory diseases. Recent WHO evaluations point to the health significance of $PM_{2.5}$. In particular, the effects of long-term PM exposure on mortality (life expectancy) seems to be attributable to $PM_{2.5}$ rather than to coarser particles.

2.2.1.2.2 Current air quality requirements based on visibility control

The measurements of the visibility factor have a strong relationship with the concentration of coarse particulate matters (PM_{10}) or dust. In most of the tunnels, there is a feedback system so that high concentration of pollutants triggers the ventilation to increase the visibility level inside the tunnel. These measurements are required as a guarantee for an acceptable level of visibility and are not related to the aspect of human well being. However, if the tunnel is located in an urban area, the outside environment can be dangerous for inhabitants due to the continuous effect of low emission concentration.

In Rijkswaterstaat documents it is stated that there is a correlation between the visibility factor and NO_2 [23]. Unfortunately, this is a very rough estimation and there is a high probability that in the near future the new regulation will be applied, that will be based on more precisely calculations. Nowadays in the Netherlands, during normal operation conditions, the ventilation systems in the tunnels are working at maximum 30% of the installed power. However, according to the tunnel specialists, most of the time the ventilation system is not turned on at all, only during calamity situations.

There are hardly any examples in the world of the use of contaminant removal technologies applied in the tunnels for an external air quality purposes. Only Japan, Norway and recently Italy and Spain have taken this approach to meet environmental performance objectives [24]. In the Netherlands the only example is the Coentunnel, where the special shafts with height of 25 m are designed to disperse the emissions into the atmosphere. However, these emission shafts consume a large amount of energy; i.e. 40% of the total tunnel consumption [2].

2.2.1.2.3 Air quality requirements based on visibility and gas emission control

This type of control is more environmental friendly and helps to keep the tunnel users out of danger. To keep emissions at acceptable level tunnel ventilation must provide the required fresh air flow in the tunnel. The required amount of fresh air for a given traffic situation in the tunnel depends on the number of vehicles as well as on the average emission per vehicle together with the admissible concentration for this particular type of emissions. The respective calculations are presented in Appendix I. The calculation of the required fresh air flow for each type of emission is based on Permanent International Association of Road Congress (PIARC) guideline [22].

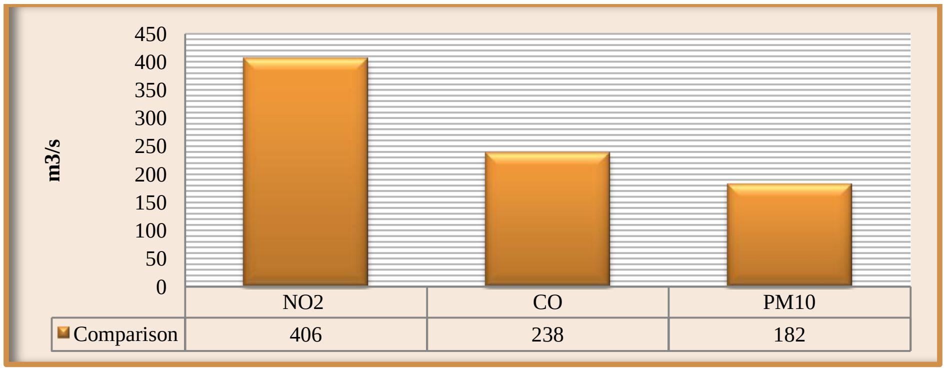

Figure 9 Required fresh air flow for different type of emissions, m^3/s

In the calculation the piston effect is taken into account. Piston effect is the result of traffic flow in the tunnel. It depends on vehicle speed, vehicle size and the vehicle spacing. In [17], the piston effect has been investigated on a 1/20 scale model tunnel and model vehicles. The results of the study show that for uni-directional tunnel with the small vehicles that have speed of 40 km/h and spacing of 2 m between each consecutive one, the measured maximum air velocity caused by piston effect is 2.25 m/s. However, the space between vehicles such 2 m seems not realistic; thus, it is assumed as 10 m. According to Rijkswaterstaat the piston effect in highway tunnels is 4-5 m/s. In the current research the piston effect is taken as an average of these statements, 3 m/s. Thus, based on the maximum among the required air flow for each type of emissions and taking into account the contribution of the piston effect, the ventilation system should generate the air flow velocity of 2.4 m/s.

2.2.2 Energy consumption estimation of ventilation system based on different air quality control systems

In Table 10 the estimated number of jet fans which should be turned on during the rush hours to keep emissions under limit. The calculations of the number of jet fans and their consumption are based on the generated air flow in the model tunnel. More detailed information is in Appendix I.

Table 10 Schedule of the ventilation system operation in the tunnel tube (power of jet fan unit is 30 kW)

Time	Number of ventilation to be turned on	
	Visibility control (nowadays situation)	Visibility and gas emission control
7 am – 11 am	1 (works on 50%)	6 (work on 100%)
11 am – 4 pm	0	0
4 pm – 20 pm	1 (works on 50%)	6 (work on 100%)
20 pm – 7 am	0	0

Figure 10 shows the results of simulation the annual consumption of the model tunnel based on different control systems. More detailed information about the simulation inputs given in Appendix I.

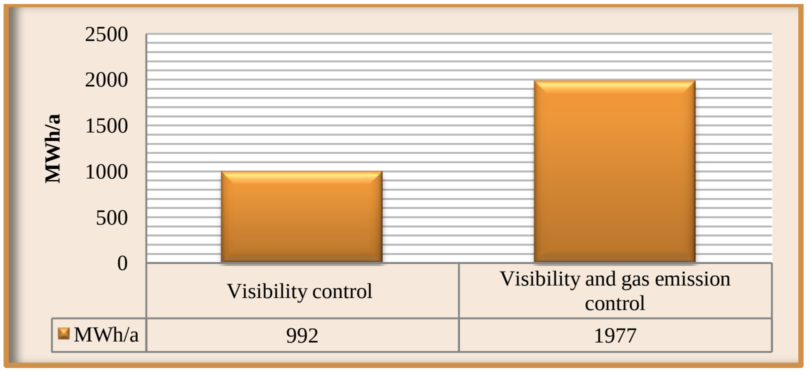

Figure 10 Simulation results of annual energy consumption of the model tunnel based on different air quality control systems

2.2.3 Summary

The simulated total energy consumption of model tunnel based on the visibility control corresponds with the total energy consumption in Vlaketunnel and Heinenoordtunnel, the Netherlands. As it can be concluded from Table 10, if new requirements would be established it would be necessary to increase the output power of ventilation on almost 12 times more to provide the required fresh air flow. This action would increase the total tunnel energy consumption on almost 100%. However, increasing the ventilation is not the solution for the air quality problem. Therefore, the solution proposed in the current project is to implement air cleaning technologies.

2.3 Air cleaning system design

As an alternative solution to improve air quality, the air cleaning system is proposed. This option would improve the air quality inside the tunnel and reduce the environmental impact of tunnel pollutions. In this case there is no need for longitudinal ventilation since the air flow due to the piston effect would be enough. However, additional ventilation is required to overcome the pressure drop caused by air cleaning installations.

2.3.1 Possible air cleaning system components

The following Table 11 lists the contaminants and possible air cleaning technologies.

Table 11 Technology for emission control inside and outside the tunnel

Contaminant	Air cleaning technology
Carbon monoxide	No known removal technology currently available to use in road tunnels
Nitrogen oxide	Adsorption system (active coal, zeolite, polymers) and/or Pulsed corona plasma processing system.
PM_{10} and $PM_{2.5}$	Electrostatic precipitator (ESP), Pulsed corona plasma processing system and/or mechanical filters.

2.3.1.1 Electrostatic precipitator

This technology is already in use in Japan, South Korea, Norway, Australia and several Europe countries. The system is generally installed to improve visibility.

Efficiency

Efficiency of the ESP system varies according to the parameters such as airflow speed, composition sizes and concentration of particulate matters. According to [24] the decrease in the particle size of pollutions reduces the treatment efficiency.

Table 12 ESP efficiency [24]

Size, µm	Content (by weight), %	Efficiency, %
<2.5	30	54-91
2.5-10	60	94-99
>10	10	>99

According to [25] the air flow velocity in ESP must be very high, typically 9 m/s or more. The latest standard determines airflow volume 7.2 m^3/s with velocity 13 m/s. This limitation was established since the owner wants to reduce the tunnel auxiliary space due to civil cost of road tunnel is very expensive. Thus, the ESP is required to treat the large volume with a very high velocity in the limited space [26].

Maintenance

Filter maintenance and regeneration are crucial factors in system's long term benefits estimation. Maintenance requires use of auxiliary equipment. This equipment varies depending on whether filter regeneration is based on wet or dry system. The principle of wet regeneration is that filters are rinsed with water. Then the treatment water is collected and filtered in order to extract any particulate matters. Dry regeneration of filters involves dry cleaning using the air jets. Mitsubishi Heavy Industries gives a requirement of 13 min drying time. The frequency of cleaning depends on number of parameters (airflow, particulates concentration, etc.), but in generally one cleaning cycle should be done every 1 to 7 days [25].

Energy consumption estimation

In this chapter, the power consumption of the ESP installation is estimated. Based on [27] the power consumed by ESP units is 100-300 W per m^3/s. ESP is assumed to be installed in by-pass with the cross area $30m^2$.

Equation 6

$$Q = v * A$$

Equation 7

$$P_{ESP} = N * P_{unit}$$

Equation 8

$$N = Q_{tunnel\ tube} / Q_{via\ unit}$$

Equation 9

$$P_{vent} = \Delta p * Q_{by-pass} * N_{rows}$$

Where:

Δp = total pressure drop of ESP units standing in a number of rows, Pa
Q = air flow, m^3/s
v = air flow velocity, m/s
A = cross area, m^2
N = number of rows of ESP units in a by-pass.
P = electric power, W

Table 13 Power estimation for the electrostatic precipitator in the model tunnel [27]

ESP installation	
$L_{tunnel\ tube}$, m	1000
$Q_{via\ unit}$, m^3/s	7.2
P, $W/m^3/s$	100-300
P_{unit}, W	720-2160
$v_{tunnel\ tube}$, m/s	3
$A_{tunnel\ tube}$, m^2	75
$Q_{tunnel\ tube}$, m^3/s	225
$A_{by-pass}$, m^2 (assumed)	30
$v_{in\ by\ pass}$, m/s (assumed)	9
$Q_{by-pass}$, m^3/s	270
N of ESP unit	31
P_{ESP}, kW	23-68
ESP unit area, m^2	1
N of unit in a row	30
N of rows	1

Table 14 Power estimation for the additional ventilation for ESP in the model tunnel

Additional ventilation	
Δp_{total}	250
P_{vent}, kW	68

$$Total\ power\ range = 90 - 135kW$$

In the new model tunnel design the air would be circulated between the tunnel tubes. Thus, the working time of ESP can be derived from Equation 10:

Equation 10

$$T = 2 * V_{tunnel\ tube} / Q_{by-pass}$$

The assumption made in this study that the air in the tunnel should be cleaned twice per day after morning and evening rush hours.

$$T = 0.3\ hours$$

Cost

There is not much data available about the initial and the operational cost. The data presented below refers to the [24] and should be examined with caution.

According to [24] in Eastlink tunnel in Australia the annual operation cost of ESP estimated approximately as 385 k€, for treated air flow of 850 m^3/s. This cost includes additional energy requirements for ventilation, which is approximately 190 k€. In Japan, the cost of the ESP maintenance is around 46 k€ per year for the filtration of an air flow of 700 m^3/s during nearly 24 hours per day. In addition, the installation cost is around 3.85 million euro.

Table 15 Cost estimation of ESP technology for model tunnel based on [24]

Technology	Purchase cost & installation, k€	Installation cost, k€	O&M per year (without electricity bills) , k€
ESP	1237.5	n/a	101.9

Table 16 Total energy cost for ESP. Assumption: tunnel tube is cleaned twice per day

Energy cost	kWh per day	MWh per year	Annual cost energy cost, k€
ESP (300 $W/m^3/s$)	20.8	7.6	0.8
ESP (100 $W/m^3/s$)	6.9	2.5	0.3
Ventilation	20.8	7.6	0.8

$$Total\ energy\ cost\ range = 1.1 - 1.7\ k€/a$$

2.3.1.2 Pulsed corona processing technology with longitudinal ventilation system

This technology is innovative for tunnel application and can be used in the tunnels with high gas emission concentration. There was a pilot project in The Netherlands made by Eindhoven University of Technology in Dommel tunnel, Eindhoven. For this pilot project the gas emissions was generated by purpose. Pulsed corona processing technology uses “cold” plasma to convert exhaust gases into harmless for human health components. The working principle is the same as in electrostatic precipitator. Thus, the ability and efficiency for PM removal is more or less the same. However, due to the higher density of the generated plasma, corona plasma technology is able to chemically destroy the NO_x.

Efficiency

The efficiency of $PM_{2.5}$ -PM_{10} removal is 90 %, but the smaller size of the particulates results the lower efficiency of the system. If the size of PM is less than 1 µm the efficiency drops until 60% . According to the system performance, we can see that it will be good application for tunnels with low visibility or with high $PM_{2.5}$ -PM_{10} concentration.

Table 17 Efficiency of the corona plasma reactor in relation with emission type [28].

Size, µm	Efficiency, %
$PM_{0.25}$ - $PM_{1.0}$	60
$PM_{1.0}$ - $PM_{2.5}$	90
$PM_{2.5}$ - PM_{10}	90-95
NO_x (concentration is between 3-10 ppm)	80

Yet, the 80-95% of diesel pollution is ultrafine particulates. Thus, considering the human wellbeing and the impact of ultrafine particulates (less than 0.1 µ) on the human health, one of the solutions could be to use corona plasma technology together with the mechanical filters. These filters must be able to capture the particulates which are smaller than 0.1 µ.

Energy consumption estimation

It is proven that the system is efficient if NO_x concentration is more than 3 ppm. The energy density of 5 J/L is enough to remove the NO_x emission with a concentration between 3 and 10 ppm. Above 10 ppm, the required energy density to remove NO_x is 10 J/L. The efficiency of the system in this case is 80%. In case of low concentration of NO_x, the system is not efficient because of the little amount of N_2 production during the reaction. During the day time the average number of vehicles in the tunnel tube is assumed as 4700 per hour. As it is mentioned earlier in the chapter "Energy consumption estimation of ventilation system based on different air quality control systems", the air velocity caused by moving vehicles is 3 m/s. Hence, the air flow of 225 m^3/s requires a lot of power to be treated by corona plasma. To decrease the power consumption for corona plasma it is suggested to decrease the air flow velocity in the by-pass where the installation can be located. According to [28] the efficiency of corona increases if the emission concentration increases as well. Therefore, a solution can be a recirculation the air in the tunnel before extraction it into the by-pass. The air flow velocity in the by-pass should be very low. However, in this case the duration of an air cleaning process would dramatically increase. The consumption of corona reactor can be found as:

Equation 11

$$P = Q * 10^3 * E$$

Where:

Q = air flow, m^3/s
E = energy density, J/L
P = electrical power, W

Table 18 Power consumption estimation for corona plasma

Corona reactor	
$L_{tunnel\ tube}$, m	1000
$v_{tunne\ tubel}$, m/s	3
$A_{tunnel\ tube}$, m^2	75
$Q_{tunnel\ tube}$, m^3/s	225
$v_{by\text{-}pass}$, m/s	0,5
$A_{by\text{-}pass}$ (2m*20m), m^2	30
$Q_{by\ pass}$, m^3/s	15
E, J/L	5-10
P, kW	75-150
N unit (30 kW)	3-5

To remove the ozone produced by corona reactor it is necessary to install the active coal bed behind the reactors. The active coal bed has a pressure drop of 250 Pa so that it is necessary to use the additional ventilation. The power for additional ventilation is found by:

Equation 12

$$P = Q_{by-pass} * \Delta p * N$$

Where:

$Q_{by-pass}$ = air flow in by-pass, m^3/s
N = number if active coal beds in a row
Δp = pressure drop for active coal bed, Pa

Table 19 Power consumption for additional ventilation

Parameter	Value
N	1
Δp, Pa	250
P, kW	3.8

The total power consumption for the corona plasma installation is between:

$$P = 79 - 154\ kW$$

The working time of corona plasma can be derived from Equation 10. It is also assumed that air should be cleaned twice per day after morning and evening rush hours.

$$T = 5.6\ hours$$

Maintenance

Maintenance of the corona plasma reactor means that after some time the nitric acid must be removed from the reactor's wall. Moreover, the active coal beds should be partly replaced every year according to corona plasma manufacturer [28]. The duration of working life depends on the emission concentration level.

Cost

The cost of corona plasma reactor is 150-200 k€ for unit with power capacity of 30 kW. In [28] the cost for three active coal beds is given as 75 k€. And the yearly replacement cost for active coal is 8 k€ per unit. Furthermore, the operation and maintenance should be considered. These costs are starting from 50 k€ per year for 3 unit x 30 kW system and include the costs of regular maintenance, cleaning, renovating plasma switch, preventive measures, partly replacement and project costs.

Table 20 Cost estimation of corona plasma technology for model tunnel based on [28]. Corona plasma unit (3 x 30 kW) cost is 150-200 k€

Technology	Purchase cost, k€	Installation cost, k€	O&M per year (without electricity bills), k€
Corona plasma reactor (3 x 30kW)	450-600	n/a	50
AC	75	n/a	24

Table 21 Total energy cost for corona plasma (E=5 J/L) Assumption: tunnel is cleaned twice per day, emission concentration less than 10 ppm

Energy cost	kWh per day	MWh per year	Annual cost energy cost, k€	Total, k€/a
Corona reactor	416.7	152.1	16.7	17.6
Ventilation	20.8	7.6	0.8	

2.3.1.3 Mechanical filters

Mechanical filters with nano-fiber technology are able to remove the PMs which are less than 1 micron. This type of filters can work alone or together with electrostatic precipitator or corona plasma technology to improve the overall cleaning efficiency from particular matters. Power consumption estimation in Table 22 is based on data from [29].

Table 22 Power consumption estimation of mechanical filter for tunnel tube

Parameter	Value
$Q_{via\ filter\ unit}$, m^3/h	10600
$Q_{tunnel\ tube}$, m^3/s	225
N of filters	76
Δp, Pa	75
$P_{additional\ vent\ for\ tunnel\ tube}$, kW	17

Equation 13

$$N_{of\ filters} = \frac{Q_{tunnel\ tube}}{Q_{via\ filter\ unit}}$$

The Ultra-Web filters are replaced after 6000 hours. Replacement costs are 145 €. Labor rate equals 55 € per hour, filters are replaced at a rate of 16 filters per hour [29].

Table 23 Costs for Ultra-Web filters for tunnel tube [29]

Purchase cost, k€	Installation cost, k€	Life time, h	O&M per year (without electricity bills) , k€
11.1	0.258	6000	n/a

2.3.1.4 Active coal

Active coal (or active carbon) is commonly used for removing the NO_x emissions. Active coal is the adsorbed material which holds physically the emission and can be released (desorbed) rather easily by either heat or vacuum. Adsorbers have been used principally to control the emissions. Carbon is activated by the pyrolysis of coal, wood, bark, coconut husks, etc. to remove all the volatile material as a gas or vapor, and leave only the carbon. The emissions typically reduces the concentrations from between 400 and 2000 ppm to under 50 ppm [30]. Power consumption estimation in Table 24 is based on data from [28].

Table 24 Power consumption of Active coal bed for tunnel tube

Parameter	Value
$v_{tunnel\ tube}$, m/s	3
$A_{tunnel\ tube}$, m^2	75
$Q_{tunnel\ tube}$, m^3/s	225
Δp, Pa	250
$P_{additional\ vent\ for\ tunnel\ tube}$, kW	56

Table 25 Costs for Active coal bed for tunnel tube [28]

Purchase cost, k€	Installation cost, k€	O&M per year (annual replacement cost) , k€
75.0	n/a	24.0

2.3.2 Design of air cleaning systems for Zero Energy Tunnel concept

Based on the results of energy consumption analysis made in this section, it can be concluded that mechanical filters and adsorption technology (active coal) are more preferable solution from power consumption approach. However, they require an often replacement which influences on maintenance and investment aspects. To prevent often replacement of mechanical filters and active coal beds it is recommended to combine them with either electrostatic precipitator or pulsed corona plasma technology. In the project the tunnel scheme is developed for two air cleaning system designs. The working principle of air cleaning installation is presented in a Figure 11. The calculation results of installed power of each air cleaning system design are presented in a Table 26.

Design 1: Electrostatic precipitator + Mechanical filters + Active coal

Design 2: Corona plasma + Mechanical filters + Active coal

Table 26. Annual energy consumption for different air cleaning designs (ESP consumption 100 W/m^3/s, NO_x concentration between 3 and 10 ppm)

Air cleaning design (for tunnel tube)	P_{tot}, kW	Daily working time, h	Daily energy consumption, kWh	Annual consumption, MWh
Design 1	178	0.3	55	20.1
Design 2	80	5.6	444	162.0

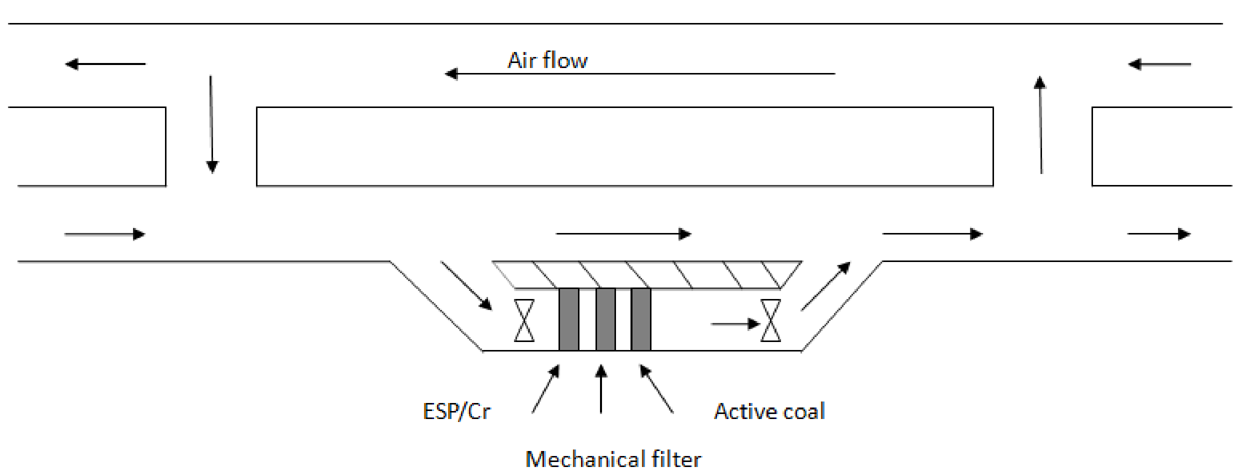

Figure 11 Working principle of the air cleaning installation in the bypass. The air flow in the model tunnel is 225 m^3/s (only piston effect). The air is recalculated between the tunnel tubes

Table 27 Annual total cost for tunnel tube. O&M cost of mechanical filters are not taken into account. Assumptions: Energy cost 0.11 €/kWh. Systems clean the total air flow in the tunnel tube twice per day. The jet fans cost are not taken into account.

Air cleaning design (for tunnel, 2 tubes)	Purchase & installation cost, k€	O&M (yearly cost), k€	Annual energy cost, k€	Annual total cost, k€
Design 1	1323.6	125.9	2.2	128.1
Design 2	536.1	74.0	17.8	91.8

2.3.3 Summary

For the Zero Energy Tunnel concept two air cleaning systems are proposed. In principle, based on the research, the air cleaning system of Design 1 is a more appropriate solution for a highway tunnel. This conclusion is based on the fact that the duration of air cleaning process by corona plasma is much longer. It is related to a large air flow in the tunnel caused by the heavy traffic. Another reason is that this system is efficient if the NO_x concentration is more than 3 ppm, this value is quite high for this type of emissions. However, for tunnel with less air flow (i.e. city tunnel) it is a good and an innovative solution to solve the problem of air quality, and the energy consumption for this design would probably be less.

2.4 Design of heat extraction system

Heat, which is generated in a process of fuel combustion wasted into the environment even though it could be reused for some useful and economic purpose. The strategy of how to recover this heat depends both on the temperature of the heated air and the economics involved. The thermal energy can be used for water distribution for the area nearby, space heating, or other purposes. Another solution is to store the heat as a daily or seasonal thermal energy storage using appropriate storage materials. Thanks to the combustion process in cars' engines there is a temperature raise for several degrees. The air recirculation between the tunnel tubes would help to get an efficient temperature raise for heat extraction. The idea of heat extraction is presented on Figure 12.

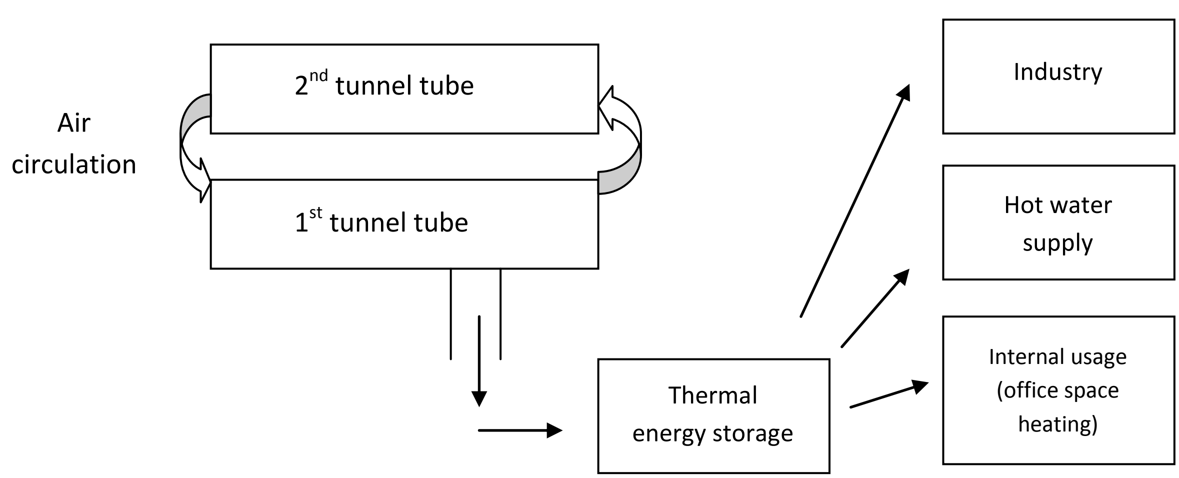

Figure 12 Draw of heat extraction concept

2.4.1 Estimation of heat generated by tunnel traffic

By using the Equation 14 the thermal energy from combustion process is defined as:

Equation 14

$$Q_{veh} = C * D * q_{comb} * v$$

Where:

Q_{veh} = the thermal energy from vehicle, J/s
C = the fuel consumption, m^3/km
D = the fuel density, kg/m^3
q_{comb} = the combustion energy, J/kg
v = vehicle speed, m/s

In Table 28 the initial data of different kind of fuel is presented, [31], [32], [33].

Table 28 Heat exhausted from vehicles engines

Passenger car (gasoline)	
Density [kg/m^3]	737.2
Combustion energy, [MJ/kg]	47.3
Consumption, [l/km]	0.08
Passenger car (diesel)	
Density [kg/m^3]	850
Combustion energy, [MJ/kg]	44.8
Consumption, [l/km]	0.08
Busses and trucks	
Density [kg/m^3]	850
Combustion energy, [MJ/kg]	44.8
Consumption, [l/km]	0.11

Table 29. Thermal energy generated by each type of vehicles in the model tunnel tube. Estimation is based on the fuel consumption.

Type of car	Thermal energy from vehicles, kJ/s
Passenger car (gasoline)	31.0
Passenger car (diesel)	33.8
Busses and trucks	46.5

Assumptions:

1. 70% car (35% diesel, 35% gasoline), 30% buses and trucks
2. The heat dissipation inside the tunnel is 85%

3. The average length for car is 4 m; for trucks and bus is 10 m. The distance between the vehicles is 10 m
4. The average air flow velocity due to piston effect is 3 m/s [17].

Table 30 Possible extracted thermal power in one tunnel tube

Thermal power	Value
From combustion process, MW	2.3
Extracted from the tunnel tube, MW	0.3

The temperature raise of air inside the tunnel tube is estimated from Equation 15:

Equation 15

$$L = Q/(C_p * \rho * (T - T_0))$$

Where:

L = air volume for air velocity of 3 m/s where piston effect taking into account = 225 m^3/s
Q = heat power extracted from tunnel, W
C_p = specific heat capacity air = 1.005 kJ/kg* K
ρ = density of air = 1.2 kg/m^3
T = heating air temperature, ^0C
T_0 = ambient air temperature = 15 ^0C

The result for estimation the temperature raise alongside the tunnel tube is presented in Table 31. The air recirculation should raise the temperature in the tunnel up to 33-38 ^0C. The air recirculation can be done only together with air cleaning technology; otherwise there would be an emission concentration raise inside the tunnel.

Table 31 The temperature raise alongside the tunnel tube. Assumption: the average temperature during warm half year period is 15 ^oC

ΔT in one tube, ^oC	1.28
$T_{in\ the\ tunnel\ after\ recirculation}$, ^0C	33-38

On Figure 13 the schematic drawing of heat extraction installation is presented.

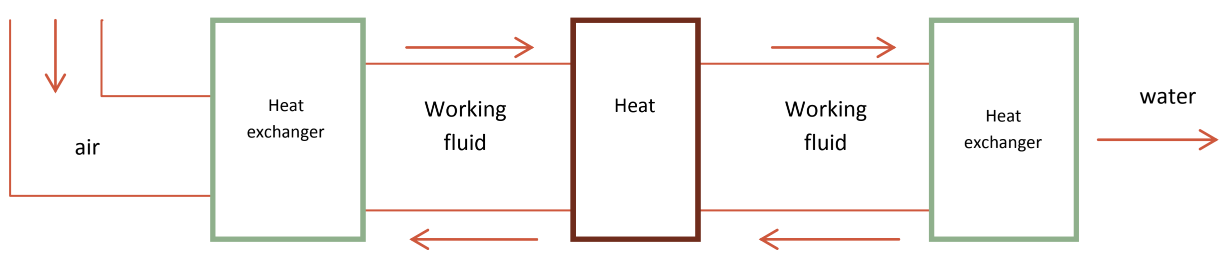

Figure 13 Draw of heat extraction system

2.4.2 Coefficient of performance (COP) of heat extraction installation

Heat pump is the main element in the heat extraction installation. To make an estimation of its energy consumption the Coefficient of Performance COP is calculated. The presented estimation was done by Carrier Air conditioning Benelux BV and can give an inside view of the power needed for heat extraction. The estimation was done for water cooled screw compressor Carrier 30HXC310-PH3opt150. The COP value includes the energy consumption of heat exchangers, heat pump and additional fans.

Table 32 PER of the heat recuperation in the model tunnel

T extracted air, °C	33-38
T output water, °C	60
P heat pump, kW	383
COP	3.65

COP helps to determine the energy consumption of the installation. For example, if $COP = 3$ that means for each 1kWh consumed by heat exchanger it would produce 3 kWh of heat.

2.4.3 Thermal storage

Three different heat storage methods exist: Sensible heat by means of increasing temperature of the object; Latent heat, by means of melting the object; Sorption heat, be means of chemical decomposition of object and endothermic reaction.

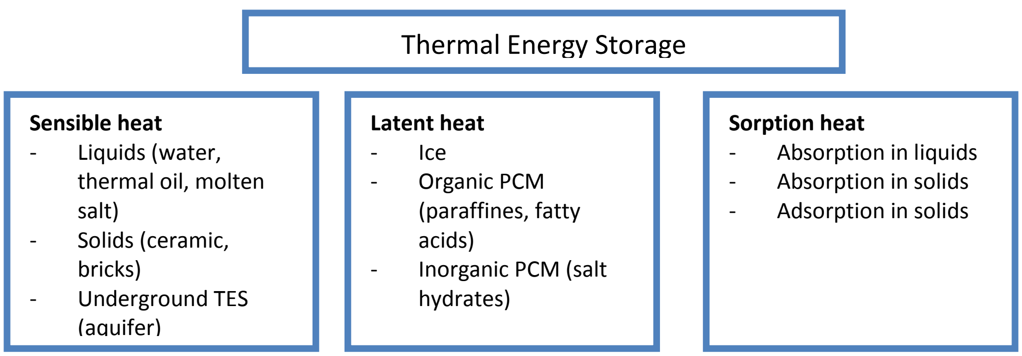

Figure 14 Different types of thermal energy storage

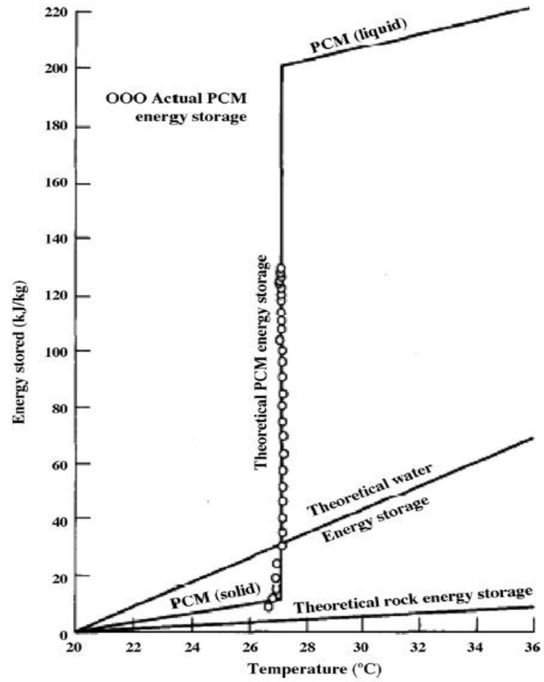

Figure 15 Performance comparison of PCM, water and rock storage systems [34]

Phase change materials (PCM) are ''Latent'' heat storage materials. The thermal energy transfer occurs when a material changes from solid to liquid, or liquid to solid. This is called a change in state, or ''Phase.'' They store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock [34]. The inorganic PCM have the highest heat storage capacity. Basically, heat is stored in the phase change of the material. Thus, a large amount of heat can be stored in a small temperature range around the melting temperature, $T_{melting}$ [35].

Equation 16

$$Q = (\rho * C_p)_{liq} * (T - T_m) * V + q_{melt} * \rho * V + (\rho * C_p)_{solid} * (T_m - T_o)$$

Where:

Q = energy content of the storage, J
C_p = heat capacity, J/(kg*K)
ρ = density, kg/m^3
V = storage volume, m^3
T_0 = ambient temperature, ^{o}C
T_m = melting temperature, ^{o}C
q_{melt} = melting energy, J/kg

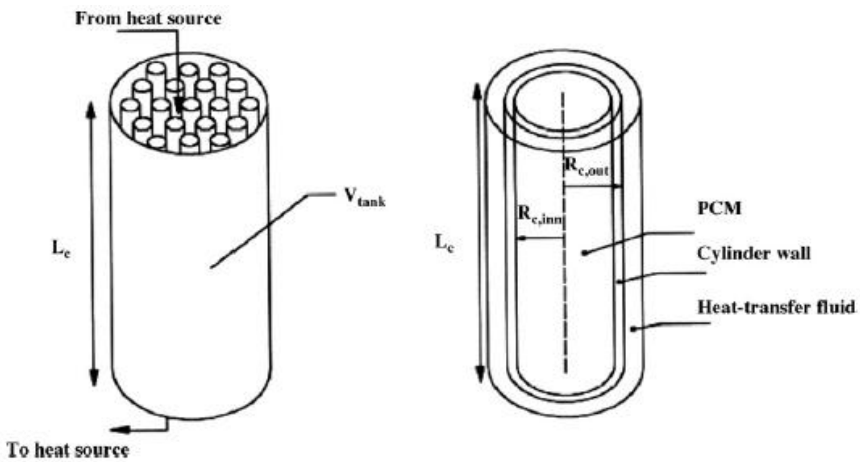

Figure 16 A cylindrical shell with PCM storage [34]

On Figure 16 the example of a cylindrical shell of PCM storage system is presented. It consists of a vessel packed in the horizontal direction with cylindrical tubes. The energy storage material (CaCl2x6H2O) is located inside the tubes and heat transfer fluid (in our case it is water) flows parallel to them [34]. The estimation of possible thermal storage capacity is presented in a Table 33.

Table 33 Inorganic PCM thermal energy storage capacity

Parameters of heat storage	Anorganic PCM ($CaCl_2x6H_2O$)
Storage Volume, m^3	20
Working fluid temperature, ^0C	60
Energy content of the storage, MJ	6512
Energy content of thermal losses (10%), MJ	651
Daily thermal energy storage, MWh (8h)	13

Advantages of inorganic PCM materials:

1. high latent heat per unit volume,
2. high thermal conductivity,
3. non-flammable.

Disadvantages:

1. corrosive to most metals,
2. suffer from decomposition and subcooling which can affect their phase change properties.

The application of inorganic PCMs requires the use of nucleating and thickening agents to minimize subcooling and phase segregation. Significant efforts are continuing to discover those agents by commercial companies [36].

2.4.4 Summary

In this section the heat extraction system is designed for the model tunnel. The results of power needed for this design will be used in the proof of concept by simulating the total energy consumption of the model tunnel.

The advice for detailed design is that the Primary Energy Ratio (PER) must be estimated before taking any decision about the heat extraction system. This estimation should be done with caution. PER is defined as:

$$PER = \frac{Q_{th}}{P_{COP} + P_{vent}}$$

Where:

P_{COP} = power consumption of the system based on coefficient of performance, kW
P_{vent} = power consumption of additional ventilation, kW
Q_{th} = delivered thermal power, kW.

There are a lot of factors which can affect the Primary Energy Ratio, i.e.:

- the location of the tunnel
- the environmental temperature
- the auxiliary energy consumption (pumps, fans)
- the technical specification of the heat pump
- the sizing and the operating characteristics of the heat pump.

2.5 Design of renewable energy generation

In this section the renewable energy generation sources chosen for the model tunnel are described. Moreover, the cost estimation analysis is presented as well. The chosen types of renewable generation sources are wind turbines and solar panels. Their capacities are based on the current model tunnel energy consumption (see Chapter 3.1) and on the energy needed for tunnel systems which is estimated in previous chapters.

2.5.1 Wind energy generation

Based on the model tunnel consumption two wind turbines with fully rated converter and a rated power of 0.5 MW are chosen. The turbines are modeled in DIgSILENT Power Factory software and consist of static generators and the step up transformers. The turbines are connected to a separated 10 kV busbar.

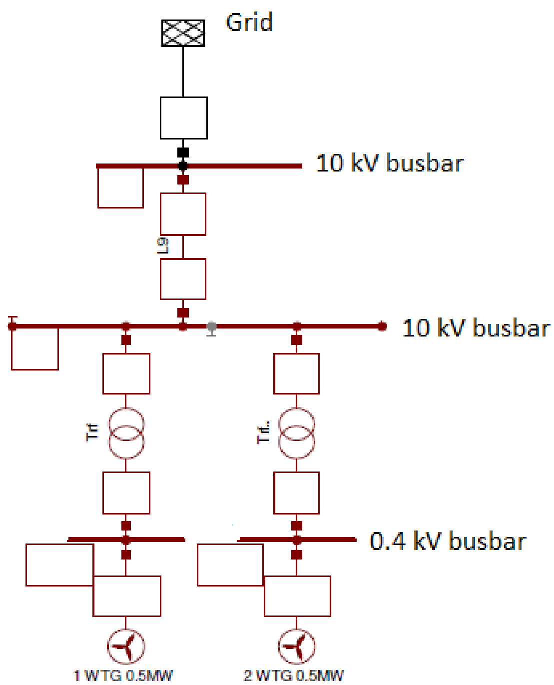

Figure 17 Wind turbines designed for the model tunnel

Wind turbine characteristics

To analyze the annual generation of the wind farm the wind speed distribution is needed. This distribution is often given as a Weibull distribution. The Weibull distribution gives for a certain wind speed a probability value. With this probability the duration of a certain wind speed over the whole year is calculated.

The power output of a wind turbine depends on the wind speed as depicted in a Figure 18. For a load flow calculation the active power output is set as a dependent value of the wind speed.

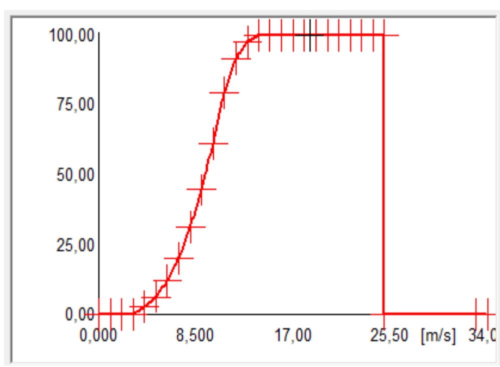

Figure 18 Power generation (%) as a function of wind speed

The dependence of the turbine's power output from a wind speed described in Table 34. These characteristics are common for most of the wind turbines. The reactive power limits are presented in Appendix II.

Table 34 Generated power (%) as a function of wind speed [37]

Wind speed, m/s	P_{output},%	Wind speed, m/s	P_{output},%
0	0	15	100
1	0	16	100
2	0	17	100
3	0	18	100
4	2,8	19	100
5	6,35	20	100
6	12	21	100
7	20	22	100
8	31,3	23	100
9	44,6	24	100
10	61,15	25	100
11	79,5	25,01	0
12	91,5	33	0
13	97,5	34	0
14	100		

Annual generation of wind turbines applied for the model tunnel

In the Table 35 the calculated annual generation and losses of chosen turbines are presented.

Table 35 Annual generation/ losses of Wind Park designed for model tunnel

Results for wind farm Sb_External Grid	
Average Power:	0,29 MW
Energy at PCC:	2548,51 MWh/a
Full Load Hours:	56,63 h

2.5.2 Solar energy generation

Solar energy generation around the tunnel is less then wind energy generation. According to the tunnel specialists in the Netherlands the maximum available area for the photovoltaic (PV) modules along the tunnel construction is around 1000 m^2. It is also possible to use the area around the tunnel (i.e. open fields in rural area, or buildings' roofs in the urban area). However, in the simulation analysis only the area that belongs to the tunnel construction is considered. In the DIgSILENT Power Factory the energy output for PV systems is chosen as an average energy output of PV systems located in the Netherlands: 1050 kWh/m^2 annual [38].

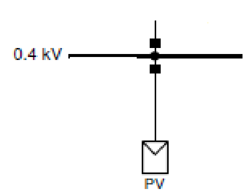

Figure 19 Photovoltaic system in DIgSILENT Power Factory.

The solar energy generation is designed as two photovoltaic systems (PV systems) connected to the both sides of the model tunnel. In reality, the available area for PV systems is the tunnel portals. PV system consists of 40 modules. One module has a rated peak power of 3.2 kW.

Table 36 Annual generation of PV systems applied for tunnel

Average power	2 x 0.06 MW
Annual energy generation	1050 MWh

2.5.3 Cost analysis

2.5.3.1 Wind energy generation cost

2.5.3.1.1 Investment and operation cost

The average cost of wind turbine varies from 900 €/kW to 1150 €/kW. The turbine itself comprises about 80% of this total cost. The rest is the cost for foundations, electrical installation, grid connection, land, road construction, consultancy and financing [39]. Another important subject is the operation and maintenance cost (O&M). According to [39] the maintenance cost can be estimated at about 20-25% of the cost per kWh produced. O&M costs include regular maintenance and repairs. Furthermore, there are additional subsidies from government as a SDE program (Stimulering Duurzame Energieproductie 2012). It is done since the cost for renewable energy production is higher than some types of conventional generation. However, it can be concluded from Figure 20 that the cost of the wind energy production is strongly decreasing.

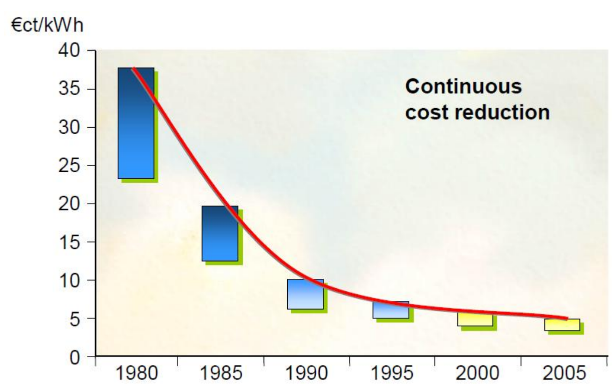

Figure 20 Wind power electricity production cost [58]

Table 37 Wind turbine investment, energy production and O&M costs

Wind turbines capacity, MW	1.0
Annual production (DIgSILENT result), MWh/a	2548.5
Cost , €/kW	900-1150
Turbines investment & installation costs, k€	900-1150
Energy production cost, €/kWh	0.05
O&M, €/kWh (25%)	0.0125

2.5.3.1.2 "Stimulering Duurzame Energieproductie (SDE)" grant

Equation 17

$$SDE = (base\ price\ (green\ energy) - correction\ price\ (grey\ energy)) * MWh$$

The maximum energy production covered by subsidies is $1\ MW * 1760\ h = 1760\ MWh$ and the duration of subsidies is 15 years [40].

Table 38 SDE Grant for wind energy generation in the model tunnel

Base price (phase 5), €cent/kWh	12
Correction price, €cent/kWh	5.8
SDE grant, k€	109.12

2.5.3.1.3 Payback period for the wind turbines

The payback period estimation is based on the assumption that electricity price is 0.11 €/kWh and increases on 3% annually.

Table 39 Payback period estimation for wind turbines (2x0.5MW)

	Costs range	
Purchase cost , €/kW	900	1150
Payback period, years	8.2	10.1

2.5.3.2 Solar energy generation cost

2.5.3.2.1 Solar energy generation investment and operation cost

According to [38] the average irradiation in the Netherlands is 1050 kWh/m^2 annual. Thus, it is possible to estimate the specific energy yield of the PV system. PR is a performance ratio. It is independent from the irradiation and it takes into account all pre-conversion losses, inventor losses, thermal losses and conduction losses. In current research the PR = 0.78 that is equal to the PR of the grid connected PV system in Utrecht, The Netherlands [38]. H_0 is a peak power of the module under Standard Test Conditions (STC), and it is independent from the area of the module.

Equation 18

$$Y_{sp} = PR * \frac{H_{irr}}{H_o}$$

Where:

Y_{sp} = the specific annual energy yield, kWh/kWp
H_{irr} = annual irradiation, kWh/m^2
H_o = peak power of the module under (STC), Wp/m^2
PR = performance ratio

A typical PV module price is between 1.5 and 3 €/Wp [41],[42]. Annual cost (depreciation + interest + maintenance) is 7% of the investment cost [38].

Equation 19

$$Production\ cost, \frac{€}{kWh} = \frac{annual\ cost}{annual\ energy\ yield}$$

Table 40 Production parameters

Parameters	Value
H_{irr}, kWh/m^2/a	1050
H_0, Wp/m^2	1000
PR	0.78
Y_{sp}, kWh/kWp,a	819

Table 41 Cost range for wind generation

	Cost range	
Purchase cost , €/kWp	1500	3000
Annual cost, €/kWp	105	210
Production cost, €/kWh	0.13	0.26

$$Investment\ cost, k€ = Average\ power * purchase\ cost$$

Table 42 Investment cost

	Cost range	
Purchase cost , €/kWp	1500	3000
PV average power, kW	120	120
PV module investment cost, k€	179.8	359.6

2.5.3.2.2 "Stimulering Duurzame Energieproductie (SDE)" grant

$$SDE = (base\ price\ (green\ energy) - correction\ price\ (grey\ energy)) * MWh$$

The maximum energy production covered by subsidies is $120\ kWp * 1000\ h = 120\ MWh$ and duration of subsidies is 15 years [40].

Table 43 SDE grant for solar energy generation in the model tunnel

Base price, €cent/kWh	15
Correction price, €cent/kWh	5.7
SDE grants, k€	11.15

2.5.3.2.3 Payback period for PV modules

It is assumed that the cost for the electricity purchase is 0.11 €/kWh and it is increasing for 3% annually.

Table 44 Payback period for PV modules

	Cost range	
Purchase cost , €/kWp	1500	3000
Payback period, years	18.5	54.6

In the calculation of payback periods for solar modules and wind turbines the current value of financial benefits is taken into account:

Equation 20

$$\lambda = \frac{1}{\left(1 + \frac{p}{100}\right)^{t}} = 0.4$$

Where:

λ = present value
t = service life [25 year]
p = interest rate [4 %].

2.5.4 Summary

In this section the characteristics of wind turbines and photovoltaic systems are described. These type of energy sources should cover the total electrical energy demand of the model tunnel on yearly basis. The cost benefits analysis shows that the payback period for wind turbines is within 10 years. However, the payback period for PV systems is longer, in range of 19 - 55 years, depending on the investment cost for PV modules. The possible benefits from selling the electricity back to the grid are not taken into account. The two wind turbines of 0.5 MW can be replaced by one turbine of 1 MW. Both of these types are available in the market. It will not affect on estimated payback period due to that the costs in this research are based on total capacity of wind turbines (which is 1 MW). However, the turbine of 1 MW is much higher than turbine of 0.5 MW. This fact can affect the visual impact. For example, in some areas the height of wind turbines can be limited by the local authorities.

2.6 Design of electrical energy storage

An energy storage is used to store the energy generated from the renewable energy sources in the tunnel in case of the grid failure or during normal operation conditions if it is more economical attractive. For example, electrical energy can be stored when price for electricity is cheaper and can be realized when purchase price for kWh would increase. Furthermore, energy storage can be used in order to smooth the load behavior of the tunnel. In this research only an emission-free way to store the electrical energy are under consideration: i.e. adiabatic compressed air, pumped hydroelectric and hydrogen energy storage. The maximum power needed for the model tunnel is 0.61 MW that is during the rush hours. It can be assumed that the maximum disconnection time with the grid is 2 hours. Thus, it is needed $0.61\ MW * 2\ h = 1.22\ MWh$ of storage capacity.

2.6.1 Adiabatic compressed air energy storage (ACAES)

During the surplus of generated electrical power or time when electricity price is low electrically driven compressors compress the air in a cavern under pressure. During this process some amount of heat is produced and stored in the thermal storage. For discharging the stored energy, the air flows via heat storage where it is heated again and expands via an air turbine, driving a generator. Thus, the heat from the compression process is utilized during expansion process. The energy density of the adiabatic compressed air energy storage and physical volume are designed for the model tunnel and presented in a Table 45.

Table 45 ACAES volume for designed model tunnel as a function of an air pressure in a cavity [43]

Pressure, bar	Energy density, kWh/m^3	Volume, m^3
20.7	2	610
79.3	7.5	163

Advantages/disadvantages

Advantages:
- emission-free energy storage
- high efficiency (around 70%).

Disadvantages:
- dependency on geographical location. It is difficult to identify underground reservoirs
- capital cost
- technology is not mature enough.

2.6.2 Pumped Hydroelectric Energy Storage

Pumped hydroelectric energy storage is the most mature and the largest storage technique available [44]. It consists of two large reservoirs located at different heights, pump and turbine units. To store the energy water is pumped from lower reservoir to a higher one, and during the need of energy water in upper reservoir is released through the turbine which is connected to the generator. The power capacity is a function of the flow rate and the hydraulic head, whilst the stored energy is a function of the reservoir volume and hydraulic head [44]. Power output and storage capacity can be calculated according to:

Equation 21

$$P_{output} = \rho * g * Q * H * \eta_{pump}/10^6$$

Equation 22

$$S = \rho * g * V * H * \frac{\eta_{turbine}}{3.6 * 10^9}$$

Where:

P_{output} = power capacity, MW

ρ = mass density of water, kg/m^3
g = acceleration due to gravity, m/s^2
Q = discharge water flow through the turbines, m^3/s
H = effective head, m
η_{pump} = efficiency of the pump, %
$\eta_{\ turbine}$ = efficiency of the turbine, %
S = storage capacity, MWh
V = volume of water that is drained and filled each day, m^3

A proposed pumped volume of water is 10 000 m^3. The efficiencies of pump and turbine are taken as 80%. In this case the energy storage facility should have 56 m of hydraulic head (the vertical distance between the upper and lower reservoirs).

Advantages:

- Pumped hydroelectric energy storage is the most mature and largest storage technique available.

Disadvantages:

- The needs of two large reservoirs with a sufficient high difference between them. The geographical surface should be taken into account to place these reservoirs.

Table 46 Pumped Hydroelectric Energy Storage characteristics

Characteristics	Value
ρ, kg/m^3	999.1
g, m/s^2	9.8
Q, m^3/s	60
V, m^3	10 000
H, m	56
$\eta_{\ turbine}$, %	80%
η_{pump}, %	80%
P_{output}, MW	26.4
S, MWh	1.22

2.6.3 Hydrogen energy storage

Hydrogen energy storage is the quite innovative and promising techniques in the field of energy storage.

There are three stages in HES:

- Creation of hydrogen
- Storage of hydrogen
- Conversion hydrogen into electrical energy.

According to [44] the production of hydrogen by electrolysis is the most proper solution from economical aspect. In this process an electrolyser uses electrolysis to breakdown water into hydrogen and oxygen. The oxygen is dissipated into the atmosphere and the hydrogen is stored for future generation. The largest commercial electrolyser systems available can produce input power of 2.5 MW. The lifetime of an electrolyser is difficult to predict due to its limited experience. However, in [44] a predicted lifetime is in the range of 5-10 years. In the Table 47 the main characteristics of proposed hydrogen energy storage are presented.

Table 47 Characteristics of hydrogen energy storage [45], [44]

Stages	Techniques	Efficiency	Life-time	O&M, % from capital cost
Production	Electrolysis	85%	5-10 years	3
Storage	Compression	49%-70%	depends on compressor type	n/a
Conversion into electrical energy	Fuel cells	22%-48%	10-20 years	n/a

2.6.4 Uninterruptable power supply (UPS)

Nowadays, most of the tunnels have chemical UPS systems or batteries that provide the power necessary for the tunnel in case of an external grid failure. Mostly, online UPS systems are used due to their higher reliability. The description and the comparison of chemical UPS systems are presented in Appendix III.

However, there are other types of non- chemical UPS systems which can be applied in the tunnel: i.e. rotary energy storage (flywheel). The Ride Through flywheel UPS system is chosen for the Zero Energy Tunnel design. A significant difference between the Ride Through and the rotary UPS system is that the mass of the flywheel is bigger, allowing for more energy storage and therefore more ride-through time during interruptions.

In [46] the analysis of the properties of using Ride Through UPS systems to support the dispersed generation is presented, particularly during disconnection from the grid and in autonomous networks. The research results show that a flywheel based Ride Through (RT) can be successfully applied to maintain frequency and voltage and thus, provide stable conditions during disconnections from the external grid. This UPS system acts as a power conditioner and an active filter in combination with the reactor (or choke coil), eliminating brief interruptions, spikes and sags from the utility [46]. In case of a failure in the external grid, the UPS system takes over the supply of power immediately, without any interruption or disturbance. The RT UPS system can be connected to the diesel generator and provide back-up power as long as there is available diesel fuel.

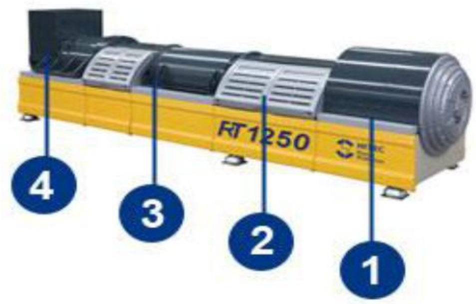

Figure 21 A HITEC RT system consists of (1) a Flywheel, (2) Pony Motor, (3) Induction coupling, (4) alternator mounted on a solid base frame [46].

The investigated RT system can provide 1 MW for 15 seconds. The alternator regulates the output voltage; the induction coupling transfers the kinetic energy of the high mass flywheel to the rotor of the generator. The coupling is controlled by a digital controller that regulates a DC current. The pony motor speeds up the flywheel until it reaches a speed of 2900 rpm. Diesel generator with RT system goes through four modes: utility mode, change-over to diesel or RT mode, diesel or RT mode, and back to utility mode. During an interruption of the power supply the system goes to the “change-over to diesel mode”, while the stored kinetic energy is being transferred from the inner rotor to the outer rotor (driving the alternator) to supply the load. During long interruptions the flywheel provides enough energy for 15 seconds until the speed of flywheel drops until 1800 rpm which is enough time to start the diesel generator. When using the UPS system, the diesel engine starts and ramps up to 1500 rpm. During the time it gets back to the utility mode, once the system detects that the utility supply is on again, it synchronizes with the system and closes the circuit breaker [46]. Thus, the RT system alone can be used for short interruptions which are less than 15 seconds. RT together with diesel generator or with generator coupled with energy storage facilities can be used for long interruptions keeping the power quality on an acceptable level.

2.6.5 Summary

In Table 48 the general characteristics of different type of energy storage systems and flywheel UPS proposed for the model tunnel are presented. The data is based on [44], [47] and [45].

Table 48 Characteristics of storage technologies

Techniques	Discharge duration	Efficiency	Life-time	Maturity
Adiabatic compressed air	4-12 h	70% and more	25-30 years	In test
Pumped hydro energy system	4-12 h	60%-80%	30-50 years	Commercial
Hydrogen	As needed	22%-48%	10-20 years	In test
Flywheel	3-120 sec	<=90%	25-30 years	Commercial

In this section three types of energy storage that are chosen for Zero Energy Tunnel concept are described. Flywheel technology is the option for UPS (or no-break) installation. It operates for 15 sec and should be coupled with diesel generation or with electrical energy storage. The choice of type of energy storage that can be implemented should be based on the location of pilot tunnel and financial aspect, and should be done during detailed design. The energy storage facilities are not implemented in the model tunnel scheme for simulation. However, the basics characteristics of these storage are estimated. The capacity of energy storage should be 1.22 MWh. Based on the required capacity, the cavity for Adiabatic Compressed Air Storage (ACAES) can vary between 163 – 610 m^3, depending of air pressure stored inside the cavity. For Pumped Hydroelectric Energy Storage the height of the water reservoir (hydraulic head) depends on pumped water volume. For the water volume of 10 000 m^3 the height should be 56 m. The advantage of hydrogen storage is that it can be used as a fuel as well. However, it should be taken in the account that the largest commercial electrolyser system available in year 2010 can produce input power of 2.5 MW [44].

3 Simulation study

In this chapter the new model tunnel scheme is developed and simulated in DIgSILENT Power Factory software, using the results of the Chapter 2 “System design”. New model tunnel scheme does not represent the complete concept of Zero Energy Tunnel due to the energy storage facilities and flywheel UPS system are not implemented in the scheme. New model tunnel scheme includes the systems, which nowadays have most of the tunnels and the systems considered in an previous Chapter 2. Simulation study is done to prove the model tunnel concept design by simulating the electric power flow and the total tunnel energy consumption and generation on yearly basis.

3.1 Developed scheme of new model tunnel

Thus, the conventional systems included in the model tunnel scheme are:

- *Drainage*
- *Ventilation (longitudinal design)*
- *Traffic installations*
- *Fires extinguish system*
- *Communication installation*
- *Building service system.*

New designed systems included in the model tunnel scheme are:

- *LED lighting*
- *Air cleaning (Design 1 and Design 2)*
- *Heat extraction*
- *Renewable energy generation (wind turbines and photovoltaic systems)*

The data of the conventional systems, their installed power and operation time that are used for the simulation are based on data for the different tunnels in the Netherlands [2], [3], [4], [5]. However, the tunnel longitudinal ventilation system assumes to be turned on only during fire. During normal operation situation there is an air cleaning system that keeps the required air quality level in the tunnel. On the Figure 22 the simplified model tunnel draw is presented. This draw gives an impression of the model tunnel scheme developed for the simulation study. The detailed model tunnel scheme is illustrated in Appendix IV.

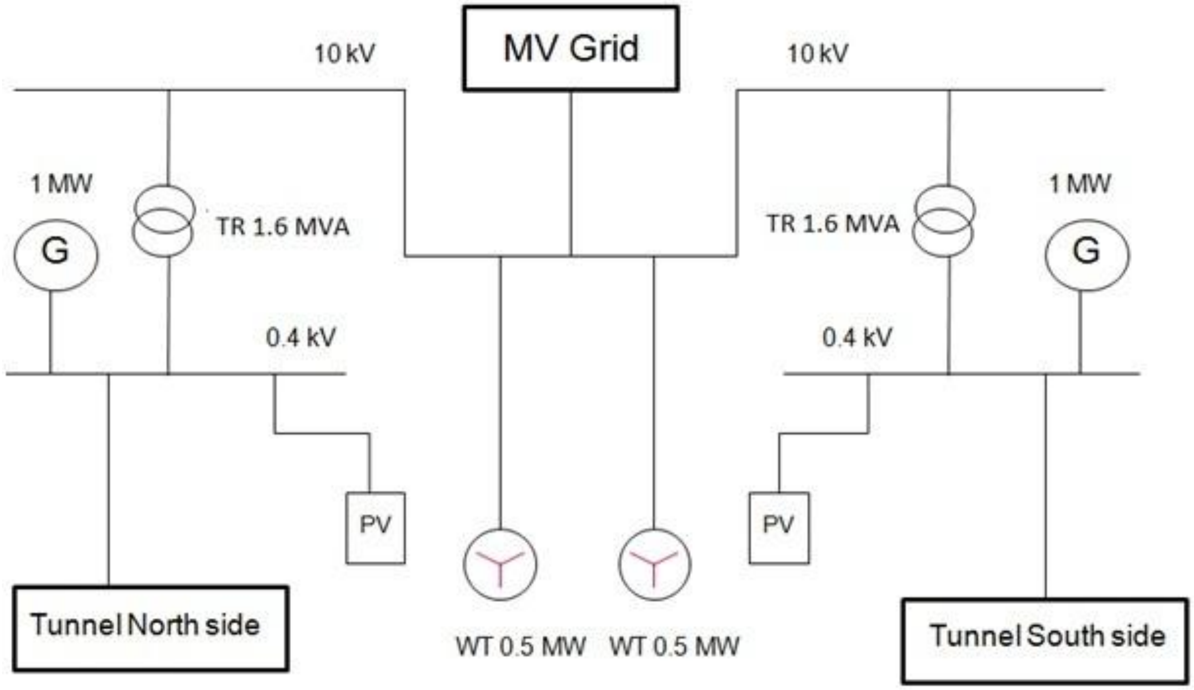

Figure 22 Model tunnel simplified draw

The data of required power for conventional tunnel systems are the average data for existing tunnels. The data for new designed systems are the calculation results of Chapter 2. The power needed for the heat extraction and air cleaning systems includes the power for additional ventilation required by these systems.

Table 49 Required power during normal operation in the model tunnel (implemented in DIgSILENT)

System	Required power, kW	Daily working time during normal operation, h
Air cleaning system. Design 1	178	2 (50% of total capacity)
Air cleaning system. Design 2	80	8
Heat extraction system	390.0	8
LED lighting system	75.0	24 (with light dimming)
Energy system	6.2	24
Drainage	9.9	24
Traffic system	3.8	24
Fire system	8.3	24
ICT	3.5	24
Building service	25.8	24
Other	1.9	24

3.2 Model tunnel electrical energy consumption and generation

The simulation study is done for two new model tunnel designs with two different air cleaning systems:

Model tunnel 1: Model tunnel with air cleaning system according to Design 1 (Electrostatic precipitator + Mechanical filters + Active coal).

Model tunnel 2: Model tunnel with air cleaning system according to Design 2 (Corona plasma + Mechanical filters + Active coal).

Based on the conclusion made in Paragraph 2.3.2 the working schedule of air cleaning and heat extraction systems is developed. In the Model tunnel 1 air cleaning system works for 2 hours per day for 50% of installed power. In Model tunnel 2 the air cleaning system works for 8 hours per day at 100% of installed power.

In Table 51 and Figure 23 the comparison is made between the Model tunnel 1, Model tunnel 2, and current model tunnel with general characteristics of highway tunnels in the Netherlands. Current model tunnel has only conventional systems: Drainage, Ventilation (longitudinal design), Traffic installations, Fires extinguish system, Communication installation, Building service system, HPS lighting system. However, the requirements for visibility and gas emission control are taken into account. In Table 50 the renewable generation sources and their capacity is presented. These data are estimated in Section 2.5.

Table 50 Renewable generation installed in the model tunnel

Wind energy generation	Two wind turbines with fully rated converter. Capacity of each turbine is 0.5 MW
Solar energy generation	PV models of 3.2 kWp each. The total area covered by PV system is 1000 m^2 and total annual generation is 1050 MWh

As it was mentioned in Section 2.5 the wind turbine power output depends on the wind speed. For simulation of the energy generated by the wind turbines the average wind speed in the Netherlands is chosen, that is 7.5 m/s. Sign "-" used for the surplus of energy while the "+" is for the amount of energy necessary to be supplied by the external grid.

Table 51 Annual energy consumed/produced for different model tunnel designs

	Total Generation MWh/a	**Total Load, MWh/a**	**Total Losses MWh/a**	**Total External Infeed, MWh/a**
Model tunnel 1	-3333	1922	180	-1232
Model tunnel 2	-3333	2083	188	-1062
Current model tunnel	0	1890	87	1977

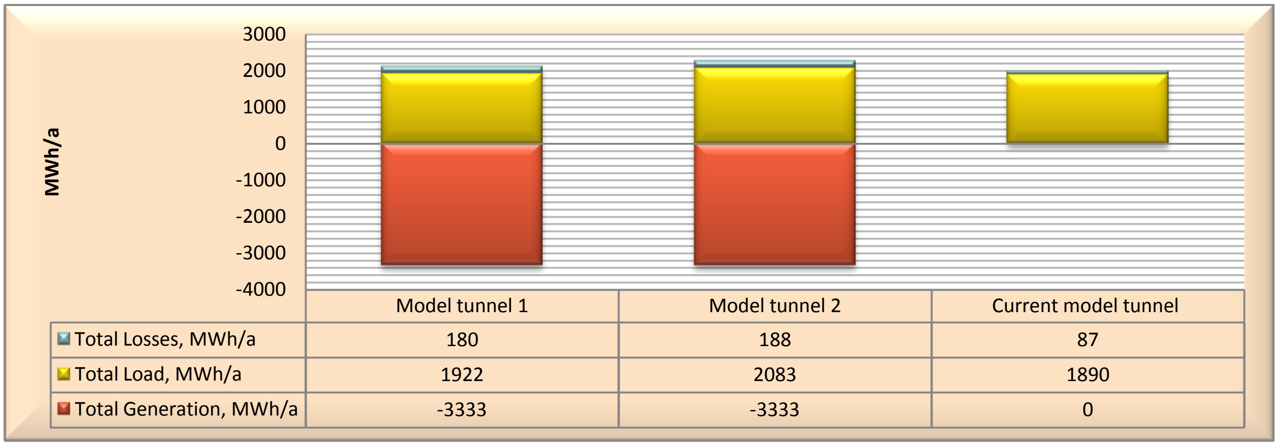

Figure 23 Comparison of annual external grid infeed. "-" means energy provided to the grid and "+" means energy taken from the grid

Table 52 Working schedule and load in % of the air cleaning and heat extraction systems

Hour of the day	Air cleaning system. Design 1, %	Air cleaning system. Design 2, %	Heat extraction system,%
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	100
8	0	0	100
9	0	100	100
10	50	100	100
11	0	100	0
12	0	100	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	100
17	0	0	100
18	0	100	100
19	0	100	100
20	50	100	0
21	0	100	0
22	0	0	0
23	0	0	0
24	0	0	0

The losses of the model tunnel are given in Table 53.

Table 53 Average losses in model tunnel designs

Scheme element	Model tunnel design 1	Model tunnel design 2	Current model tunnel
Losses of 1.6 MVA MV/LV main transformers (2 units), kW	7.21	6.75	6.36
Losses of 1.12 MVA MV/LV wind turbine transformers (2 units), kW	3.90	3.90	0

The average losses of low voltage cables vary between 0.73 and 1.96 W/m depending on the model tunnel design, and these values are common values for power cables. The losses for the medium voltage cables are very low, that they almost do not contribute to the total annual energy losses. In the most of the nowadays tunnels two or more MV/LV transformers are installed to increase the reliability of the power flow and to decrease the losses by decreasing the total length of low voltage cable connections. However, the results of simulation in DIgSILENT Power Factory software show that the share of energy losses of MV/LV transformers is almost half. Thus, the question is: would it be wise to increase number of MV/LV transformers to avoid power cable losses or not?

3.3 Power flow analysis and introduction to the power quality

Reliability of the power flow is calculated as the total percent of time when voltage is presented, and usually stated as the number of “nines” of reliability. For example, a power system that is down for 60 cumulative minutes each year would be said to be 99.98% reliable, or “three nines.” Rijkswaterstaat requires reliability in the tunnel of “six nines”, meaning that 31.5 seconds of electric power outage is allowed per year. To reserve the power that is always available in the new tunnel design, two back-up generator installations on the two sides of the tunnel are proposed. They are connected to the LV busbars to be directly available for the tunnel load. Each of the installation consists of 1 MW generator. Thus, each of the generator installations can provide the total power for normal operation in the tunnel. The simulated data for necessary power that must be provided by back-up generators are given in Table 54, provided for the Model tunnel 1, where the air cleaning technology according to Design 1 and heat extraction (HR) installations are applied. The wind turbines are connected to a separate 10 kV busbar. Thus, in case of maintenance the wind turbines can be easily disconnected. PV systems are connected to both sides of the tunnel via low voltage busbars. In Appendix IV the example of power flow analysis is shown.

Table 54 Model tunnel load variations during normal operation (Design 1)

Active power, MW	Reactive power, Mvar
0.07-0.61 MW	0.15-0.20 Mvar

To keep the power quality in the tunnel the following scenarios should be considered:

1. Normal operation without renewable generation in the tunnel
2. Normal operation with renewable generation in the tunnel
3. Short interruptions in the grid
4. Long interruptions in the grid. No surplus of generation in the tunnel

5. Long interruptions in the grid and surplus of generation in the tunnel

Scenario 1: Normal operation without renewable generation in the tunnel

The load of the model tunnel is presented in Table 55. The maximum load corresponds to the period when lighting system is working on 90% and air cleaning system together with the heat recuperation installation are working on 100% of installed power. However, the minimum load corresponds to the night time when lighting level on its minimum, and air cleaning with heat extraction systems do not work. During the normal operation the daily tunnel consumption behavior is similar for each day.

Table 55 Tunnel load during highest consumption period (Model tunnel 1)

Scenario 1	UPS	To/From Grid
Maximum load:		
- Active power		0.61 MW
- Reactive power		0.20 Mvar
- Cos (phi)		0.95
Minimum load:	-	
- Active power		0.07 MW
- Reactive power		0.15 Mvar
- Cos (phi)		0.41

It is possible to improve power factor in case of minimum load in the tunnel by introducing the shunt capacitor with step regulated output reactive power or by controlling the output reactive power from the wind turbines. However, in this case it is not necessary due to load is low. During the normal operation the model tunnel keeps connection with the medium voltage external grid, thus the reliability remains the same as in the current tunnel.

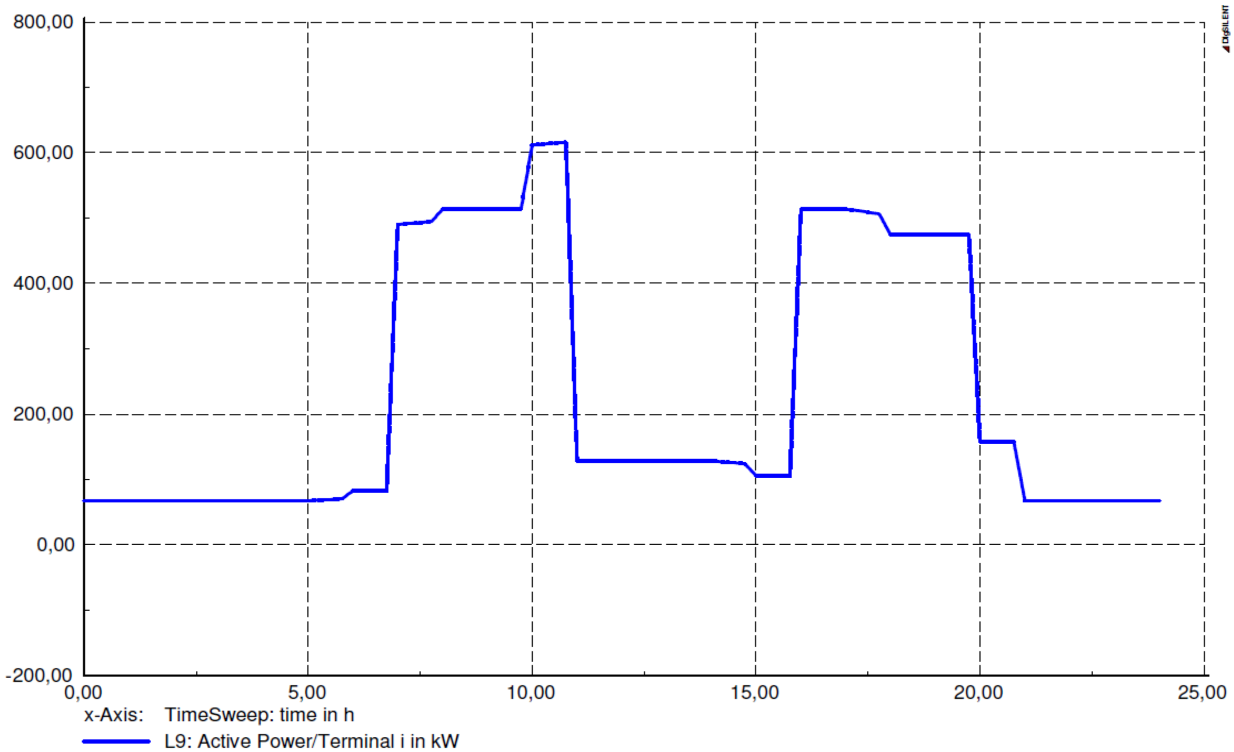

Figure 24 Daily load profile of tunnel without renewable generation, kW (Model tunnel 1)

Scenario 2: Normal operation with renewable generation in the tunnel

With renewable energy sources the generation not always matches the tunnel load. In this case the capacity of the connection between the tunnel and the external grid should be enough to bring the generated power to the grid.

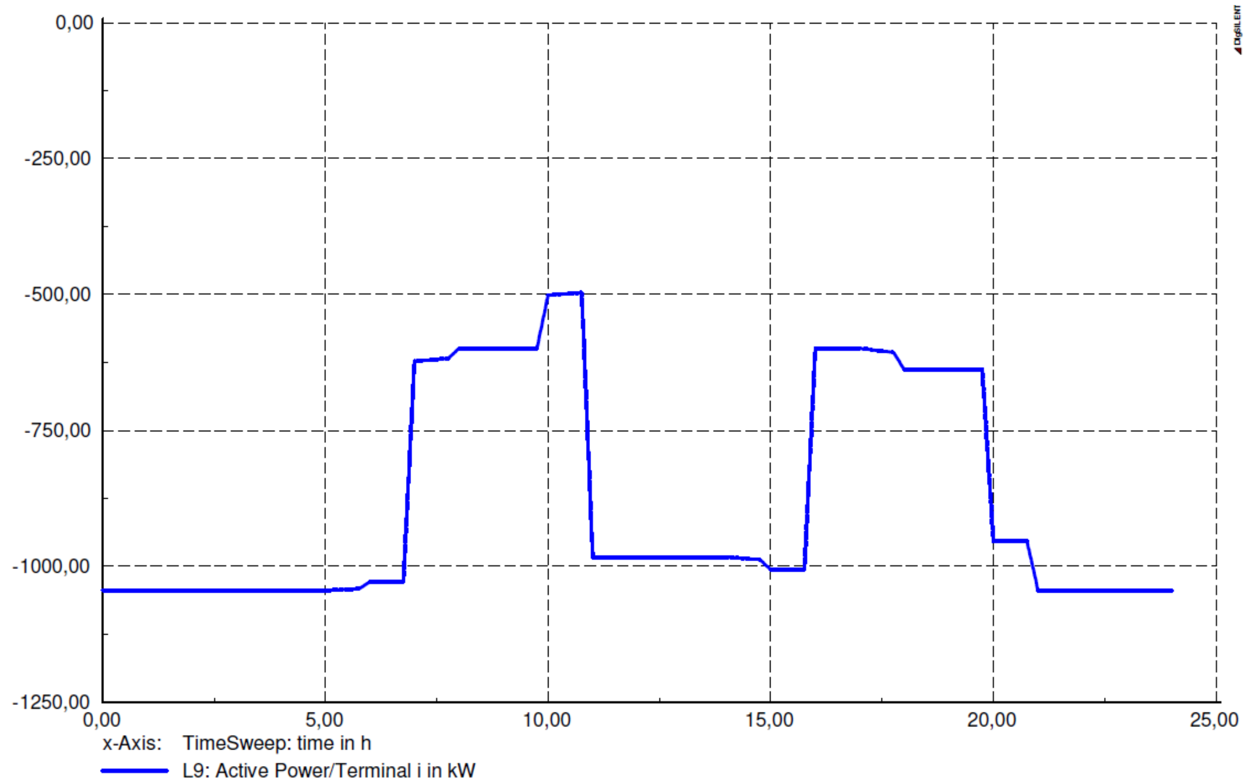

Figure 25 Daily load profile of tunnel with renewable generation, kW (Model tunnel 1,wind speed is 14 m/s)

The figure above shows daily load profile of Model tunnel 1. This load profile corresponds to maximum power output from the wind turbines during 24 hours. Table 56 and Table 57 present the data of the maximum/minimum consumed power and the maximum/minimum generated power in the Model tunnel 1.

Table 56 Power flow to/from grid at maximum load in the Model tunnel 1

wind speed 7.5 m/s and irradiation 120 W/m^2					
Scenario 2	UPS	Tunnel load	Wind generation	Solar generation	To/From Grid
Active power Reactive power Cos(phi)	-	0.61 MW 0.20 Mvar	0.26 MW 0.08 Mvar	0.12 MW -	0.24 MW 0.12 Mvar 0.89
wind speed 14 m/s and irradiation 120 W/m^2					
Active power Reactive power Cos(phi)		0.61 MW 0.20 Mvar	1.00 MW 0.30 Mvar	0.12 MW -	-0.51 MW -0.10 Mvar 0.98

Table 57 Power flow to/from the grid at the minimum load in the Model tunnel 1

wind speed 7.5 m/s and irradiation 120 W/m^2					
Scenario 2	UPS	Tunnel load	Wind generation	Solar generation	To/From Grid
Active power Reactive power Cos(phi)	-	0.07 MW 0.15 Mvar	0.26 MW 0.08 Mvar	0.00 MW -	-0.19 MW 0.07 Mvar 0.94
wind speed 14 m/s and irradiation 120 W/m^2					
Active power Reactive power Cos(phi)		0.07 MW 0.15 Mvar	1.00 MW 0.30 Mvar	0.00 MW -	-0.93 MW -0.15 Mvar 0.99

According to the Grid Code in the Netherlands all generation units connected to the network with a voltage lower than 50 kV may be operated at a power factor between 1.0 and 0.85 (lagging) measured at the generator terminals [48]. For wind park designed for the model tunnel and coupled with the grid the power factor is within acceptable level.

Scenario 3: Short interruptions in the grid

During the short interruptions in the grid which are less than 15 sec the Ride Through UPS system starts to operate. The main objective for the flywheel system is to stabilize the frequency at 50 Hz and voltage during the first seconds. After 15 seconds the flywheel's rotor starts to decelerate and both frequency and voltage collapse if grid connection is not recovered or no further decision is taken to start a back-up generator [46].

Scenario 4: Long interruptions in the grid. No surplus of generation in the tunnel

Table 58 Power generation/consumption at maximum load in the model tunnel during long interruption with external grid

Scenario 4	**Tunnel load**	**Wind generation**	**Solar generation**	**Back-up generators contribution**
Active power Reactive power	0.61 MW 0.20 Mvar	0.26 MW 0.08 Mvar	0.12 MW -	0.24 MW 0.13 Mvar

The flywheel based Ride Through UPS is used for the interruptions of less than 15 seconds. This is the time delay for the back-up generator.

Since the renewable generation is hardly controllable and there is no connection with the external grid, the back-up generator should always follow very quickly the load behavior. Furthermore, the back-up generators must have voltage and frequency controllers. These measurements help to avoid the possible damages of tunnel electrical and electronic equipment and make it possible to switch back to the external grid.

Scenario 5: Long interruptions in the grid and surplus of generation in the tunnel

The maximum amount of power needed in the model tunnel is 0.61 MW in case of rush hours. It is proposed to design the electrical energy storage according to the maximum tunnel load and the interruption time with the external grid of 2 hours. Thus, it is needed $0.61\ MW * 2h\ =\ 1.22\ MWh$ of energy storage. If the tunnel design has different type of generators, the interaction between these systems needs to be considered. The common control strategy has the highest importance to keep the power quality at an acceptable level. The energy storage and back-up generators should have the frequency and voltage controllers. Moreover, they should be synchronized with the network before switching. Additionally, switching on and off the generators, heavy loads such an electrostatic precipitator, corona plasma, or capacitor bank, can cause a transient phenomena. The proper measures must be applied in the detailed design of the tunnel. Increasing number of power electronics in the tunnel due to implementing LED lighting system or reactive power compensator would increase the harmonic distortion. The filtering components should be added to the electrical equipment.

3.4 Summary

Based on the simulation results of annual energy generation and consumption it can be concluded that:

- The annual energy consumption difference between the model tunnel with LED lighting, air cleaning and heat extraction systems and the current model tunnel with HPS lighting and longitudinal ventilation based on the visibility and gas emission control, is small
- The capacity of chosen wind and solar energy generation sources is enough to cover new model tunnel annual energy consumption
- The transformers losses on yearly basis are high. The choice of number of MV/LV transformers and their capacity should take this fact into account in the detailed design.

Moreover, when the tunnel design has different types of generators (i.e. renewable energy sources, UPS, back-up diesel generators or generators coupled with the energy storage), the interaction between them needs to be considered. For this, the common control strategy has the highest importance for keeping power quality at an acceptable level.

4 Conclusion

The Zero Energy Tunnel concept described in this report includes a lot of aspects related not only to electrical but also to mechanical and civil engineering. All the made assumptions are based on the real situations. Moreover, the investigation aim is not only to estimate the possible energy consumption reduction and to make the tunnel as a zero energy element but also to point on the environmental aspects.

The goals of the Zero Energy Tunnel project study are:

- To find possible solutions to decrease energy consumption in the tunnel
- To investigate innovative solutions to make the tunnel environmental friendly
- To implement renewable energy generation and energy storage
- To establish the needed power flow between all the components and medium voltage grid with keeping power quality at an acceptable limit
- To develop a Zero Energy Tunnel conceptual design.

The contributions of this research to Zero Energy Tunnel project goals are:

Goal: To find possible solutions to decrease energy consumption in the tunnel
Contribution: The possible energy saving for tunnel lighting system can be reached 53% by introducing LED instead of HPS lighting system. This result is correlated with the real measurements in Vlaketunnel, the Netherlands, where the implementation of LED system reduces the tunnel lighting energy consumption by 50%. Based on the simulation results the total tunnel annual energy consumption can be reduced with 12%.

Goal: To investigate innovative solutions to make the tunnel environmental friendly
Contribution:

1. Two air cleaning system designs are developed. It is done because of high possibility that the requirements from the government for the air quality would be stricter in near future and would include also gas emission control. The energy consumption of these systems does not increase noticeably the total tunnel consumption where longitudinal ventilation is used to meet air quality requirements. However, the environmental impact of tunnel pollutions can be eliminated by installing air cleaning systems.

2. The implementation of the heat extraction system in the tunnel is a good way to utilize the heat generated by tunnel traffic and gain some financial benefits meanwhile. However, during the detailed design the Primary Energy Ratio (PER) should be estimated before taking any decision about implementing the heat extraction system. This estimation should be done with caution.

Goal: To develop a renewable energy generation and energy storage
Contribution: Based on the model tunnel installed power and the energy consumption of developed in this research tunnel systems, the wind turbines and photovoltaic system are chosen with specified characteristics. The cost benefits analysis shows that the payback period for wind generation is within 10 years; the payback period for PV systems is longer, in a range of 19 - 55 years, depending on the investment

cost for PV modules. Moreover, in this report the investigation of possible energy storage facilities and their basic characteristics related to the model tunnel parameters are presented.

Goal: To establish the needed power flow between all the components and medium voltage grid with keeping power quality at an acceptable limit.
Contribution: developed tunnel scheme is analyzed in the DIgSILENT Power factory Software. The proper capacities of tunnel elements are chosen. The power flow analysis shows that there is no overloading of power cables or electrical machines. However, this analysis also shows the high losses of MV/LV transformers.

Goal: To develop a Zero Energy Tunnel conceptual design.
Contribution: Simulation study is done to prove new model tunnel concept design by simulating the electric power flow and the total tunnel energy consumption/generation on a yearly basis. The results show that the annual energy consumption difference between new model tunnel with LED lighting, air cleaning and heat extraction systems and the current model tunnel with HPS lighting and longitudinal ventilation based on the visibility and gas emission control, is small. Moreover, the capacity of chosen wind and solar energy generation sources is enough to cover the annual energy consumption of new model tunnel.

According to the results the individual goals are achieved. However, in the complete new tunnel concept design the energy saving on tunnel lighting is taken over by extra energy used for air cleaning and heat extraction systems. Thus, the new developed tunnel concept will not consume less energy, but it will also not consume noticeably more energy than current tunnel equipped with HPS lighting and where longitudinal ventilation based on the visibility and gas emission control. The advantages of the new concept design that with almost the same energy demand there is no impact on the environment and heat generated by the tunnel traffic is utilized to gain economic benefits.

Based on the current study results the scientific paper “Zero Energy Tunnel: Renewable Energy Generation and Reduction of Energy Consumption” is prepared. The paper is accepted by 47th International Universities’ Power Engineering Conference (UPEC 2012).

5 Future work

The developed concept has different uncertainties, which need to be solved during the detailed design. These uncertainties include the construction and maintenance aspects.

There are other tunnel systems that are common for tunnel design but are not considered in this research. Moreover, the other possibilities to improve the performance of the zero energy tunnel exist. For example:

- the real-time measurements of the amount and angle at which the sunlight enters the tunnel as well as daylight louvers, which proportionally reduce the amount of light and energy needed in the tunnel zones, could affect the energy consumption of lighting system
- The real-time measurements of the emission concentration in the tunnel could define the working time of the air cleaning systems more precisely
- Heat generated in operating rooms can be also utilized to gain financial benefits.

Furthermore, the electrical and electronic equipment are not precisely defined in the model tunnel, as well as energy storage and uninterruptable power supply. Thus, a complete power quality analysis is not done for developed model tunnel scheme. This is left for the detailed design. The developers of Zero Energy Tunnel detailed design should take into account that new tunnel has different types of generators (i.e. renewable energy sources, UPS, backup generators and generators for energy storage), the interaction of them has the highest importance. For this, the common control strategy for keeping power quality at acceptable level should be developed. Furthermore, the transformers losses on yearly basis can be high. The choice of number of main transformers and their capacity in the detailed design should take this fact into account.

To improve the model tunnel concept design based on these advices, the developed scheme of new model tunnels in DIgSILENT Power Factory software can be used. This should be done during the detailed design, where tunnel contractors and government should be involved.

Appendix I

Energy consumption for ventilation system

This chapter presents the calculation of the number of jet fans and required fresh air flow according to required concentration limits of NO_x for 1-2 min and CO for 5-10 min given by Aanbevelingen Ventilatie van Verkeerstunnel, and PM_{10} based on visibility factor, k= $5*10^{-3}$ m^{-1} given by Permanent International Association of Road Congress (PIARC) in [22]. The results are used for the estimation of power need for the longitudinal ventilation in the model tunnel (see Table A2 and Table A8).

Calculation of number of jet fans

The ventilation system in the tunnel is designed for the maximum air flow velocity as 2.5 m/s. For estimation the number of fans it is possible to calculate the total maximum air flow in the tunnel and divide it on the air flow processed by each jet fan. This is an approximate estimation; however the results are matching the realistic value. It is necessary to take in to account the location of the tunnel, the wind speed, pressure drop in the tunnel to calculate more precisely. This calculation must be done during the detailed design. For current project the simplified calculation is made, that are enough to estimate approximate energy consumption. The maximum air flow in the tunnel can be estimate according to:

Equation A1

$$Q = h * w * v$$

Where:

h = tunnel tube height, m
w = tunnel tube width, m
v = air flow velocity in the tunnel tube, m/s

For estimated air flow we can choose the same jet fan type as in Coentunnel in Amsterdam [49]:

Table A1 Calculation of installed power for ventilation system in the model tunnel

Parameter	Value
Air flow velocity in tunnel tube, m/s	2.5
Tunnel tube cross area, m^2	75
Maximum air flow in tunnel tube, m^3/s	187.5
Number of installed jet fans in tunnel	12
Power of jet fan unit, kW	30
Total installed power, kW	354

Energy consumption of tunnel based on visibility control

The maximum energy consumption for ventilation in the current tunnel is 8% of total consumed power, due to the current control system is based on the visibility control. However, to estimate the power consumption of the tunnel ventilation based on the visibility and gas emission control, it is necessary to calculate the required air flow in the tunnel and based on this calculation estimate needed power in percentage from the installed power.

Table A2 Systems included in the model tunnel and their power. Current situation (ventilation designed on maximum air flow 2.5 m/s, HPS lighting system, tunnel ventilation based on the visibility control)

System	Installed power,% from total installed power	Installed Power, kW	Energy consumption, % from total consumption during normal operation
Ventilation	43.9%	353.9	8.1%
Lighting	14.9%	120.1	48.6%
Drainage	15.0%	120.9	8.0%
Traffic system	2.3%	18.8	3.1%
Fire system	8.3%	67.2	6.7%
ICT	1.1%	9.1	2.9%
Building service	13.3%	107.2	21.0%
Other	1.1%	8.9	1.6%
Total	100%	806.1	100%

Energy consumption of the ventilation system based on visibility and gas emission control

Required fresh air flow calculation

The required amount of fresh air flow for a given traffic situation in the tunnel depends on the number of cars in the tunnel as well as on the average emission per car and with the admissible concentration for particular emission type. This is expressed in the following formula [22]:

Equation A2

$$Q = M * \frac{L}{V} * q * \frac{1}{Cadm - Camb}$$

Where:

Q = fresh air flow in tunnel tube, g/h
M = traffic flow in tunnel tube, veh/h
L = tunnel tube length, m
V = average speed, km/h
q = emission per vehicle. It is a table value and depends on a road gradient (in this case road gradient is zero), g/h or m^2/h.
C_{adm} = admissible concentration, mg/m^3

C_{amb} = ambient concentration, mg/m^3

For the turbidity due to diesel smoke, C_{adm} - C_{amb} is replaced by K_{adm} [22].

Table A3 Visibility coefficient

Visibility coefficient K, 10^{-3}* m^{-1}	
Free traffic	5
Daily congested traffic	7

Assumptions:

1. 70% car (35% gasoline + 35% diesel engine), 30% buses and trucks
2. For air flow calculation, *q* is chosen as average of different types of engine. According to [50] Dutch guidelines gives other specifications for large constructions concerning the maximum gradient. At a designed speed of 100 and 120 km/h a maximum gradient of 5% is acceptable for large constructions, as opposed to 3% for the common vertical stretches. A 6% gradient is being considered in the design of the 'Tweede Coentunnel' near Amsterdam. In current calculation gradient is taken as 0%.
3. NO_2 is 20% of NO_x [51].

The emission per vehicle is presented in Table A4, [22].

Table A4 Emission per vehicle according to PIARC.

Passenger car, 100 km/h							
Gasoline	q, g/h		q, m^3/h	Diesel	q, g/h		q, m^2/h
	CO	NO_x	PM_{10}		CO	NO_x	PM_{10}
US 83	82.2	36.3		EURO 2	16.8	48.7	23.81
ECE 15/04	753.4	262.9		EURO 1	23.4	54.1	29.8
ECE 15/00	2840	225		ECE 15/04 and before	68.3	87.8	66.7
Average	1225.2	174.7		Average	36.2	63.5	40.1
Busses and trucks, 80 km/h							
pre-EURO	294.6	685			294.6	685	185.7

The ambient value of CO and NO_x are based on [1] and [22].

Table A5 Admissible and ambient value of CO and NO_x

Parameter	Value
i, %	0
M, veh/h	4700
L, m	1000
V, km/h	100
C^{co}_{adm}, mg/m^3 (5-10 min)	34.84
C^{co}_{amb}, mg/m^3	5.74
C^{NOx}_{adm}, mg/m^3 (1-2 min)	1.88
C^{NOx}_{amb}, mg/m^3	0.021

Equation A3

$$Q = \max\left(Q_{NO_2}, Q_{CO}, Q_{PM_{10}}\right)$$

Table A6 Required air flow and air velocity in the model tunnel

Air flow	m^3/s
Q_{NO_2} (20% of NO_x)	406
Q_{CO}	238
$Q_{PM_{10}}$	182
$Q_{\text{piston effect}}$(v=3 m/s)	225.0
$Q_{\text{required in tunnel tube}}$	180.9

Energy consumption of a tunnel with visibility and gas emission control

According to total required fresh air flow the minimum air flow velocity is approximately 5.4 m/s. However, due to piston effect air flow velocity of 3 m/s the required air flow velocity can be reduced until 2.4 m/s. The assumption is that ventilation works only during 8 hours per day.

Table A7 Average power consumed by ventilation system based on emission control

Parameter	Value
$v^{req}_{\text{in the tunnel tube}}$, m/s	2.4
N of jet fans in the tunnel	12
P, kW	341

Table A8 Systems included in the model tunnel and their power. Future situation (ventilation designed on maximum air flow 2.5 m/s, HPS lighting system, tunnel ventilation based on the visibility and gas emission control)

System	Installed power,% from total installed power	Installed Power, kW	Energy consumption, % from total consumption during normal operation
Ventilation	43.9%	353.9	51.5%
Lighting	14.9%	120.1	25.7%
Drainage	15.0%	120.9	4.2%
Traffic system	2.3%	18.8	1.6%
Fire system	8.3%	67.2	3.6%
ICT	1.1%	9.1	1.5%
Building service	13.3%	107.2	11.1%
Other	1.1%	8.9	0.8%
Total	100%	806.1	100%

Appendix II

Reactive power limits of wind turbines

Since wind turbines with fully rated converter use power electronics for converting the output of the generator to an output with a constant frequency they have also some limitations (mainly due to current limitations). One of these limitations is the voltage dependency of the reactive power capability. This dependency is also modeled in PowerFactory and presented in Table A9.

Table A9. Reactive power capability for wind turbines [37]

	Qmin curve in [pu]			Qmax curve in [pu]		
Voltage [p.u.]	P = 0 [p.u.]	P = 0.2 [p.u.]	P = 1 [p.u.]	P = 0 [p.u.]	P = 0.2 [p.u.]	P = 1 [p.u.]
0,90	0,00	-0,28	-0,28	0,00	0,30	0,30
1,00	0,00	-0,33	-0,33	0,00	0,41	0,41
1,05	0,00	-0,33	-0,33	0,00	0,41	0,41
1,10	0,00	-0,28	-0,28	0,00	0,35	0,35

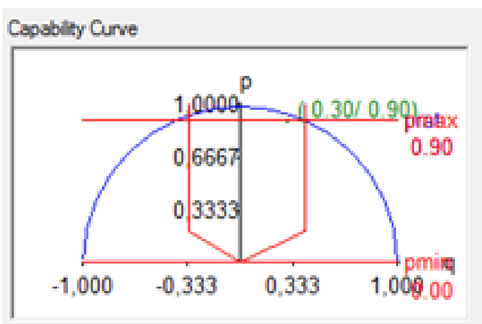

Figure A1 Capability curve for wind turbine in DIgSILENT Power Factory

Appendix III

Uninterruptable power supply (UPS)

UPSs are used to store energy when utility power is interrupted. UPS technology can be divided as chemical and non-chemical UPS. In most of the Dutch tunnels the batteries are used as a UPS. There are basically three different types of battery UPS: offline (standby), line-interactive, and online. In this appendix the descriptions of them and non-chemical flywheel UPS chosen for Zero Energy Tunnel are presented.

Chemical UPS

All battery systems are DC energy sources. There are basically three different types of devices that are commonly referred to as UPSs: offline (standby), line-interactive, and online.

Offline or Standby UPS

This UPS delivers stored power when utility power fails. The batteries are then charged when utility power is again available. Loads are normally connected directly to utility power. The schematic illustration is shown in Figure A2.

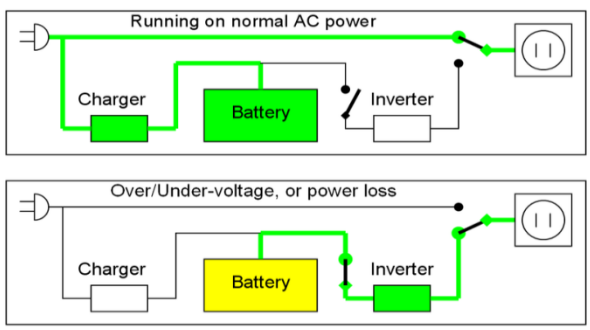

Figure A2 Offline UPS working principle [52]

Line-Interactive UPS

This form of UPS conditions the utility power by employing a ferroresonant transformer, which acts as an automatic voltage regulator between AC input and AC output. The transformer maintains a constant output voltage in case of slight voltage deviation. In case the utility voltage is interrupted or it drops too low, energy is taken from the internal battery. The working principle is illustrated in Figure A3.

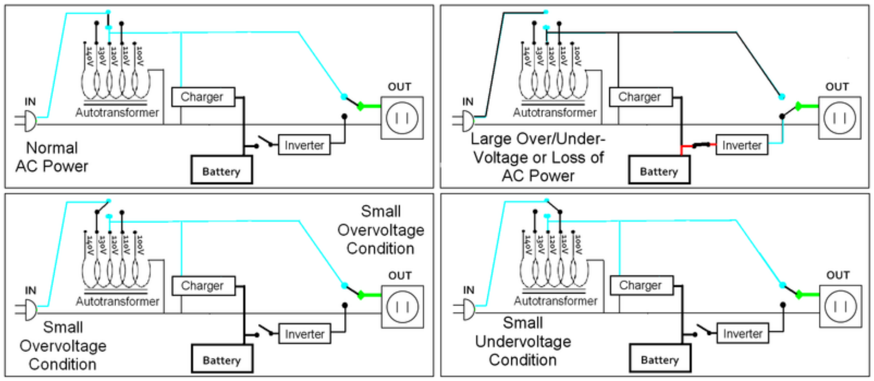

Figure A3 Line -Interactive UPS working principle [52]

Online UPS

The online UPS is ideal for environments where electrical isolation is necessary or for equipment that is very sensitive to power fluctuations. In this case the power flows via double-conversion (AC to DC, DC to AC or rectifier/inverter process). There is no transition required when the utility power is interrupted [53]. All types of chemical batteries are very sensitive to the environment temperature. The temperature is specified by manufacturer. Higher temperature shortens the life time, and lower temperature reduces capacity. Advantages and disadvantages of each type of chemical UPS is presented in Table A10.

Table A10 Summary for different type of chemical UPS technology

	Offline UPS	Line-Interactive UPS	Online UPS
Advantages	Cost is lower in comparison with other types	Employing ferroresonant transformer which can manage the voltage deviation without consuming battery power	No switching time, better reliability
Disadvantages	- Switching time. This can negatively effect on the reliability - Sensitive to the environment temperature - Life time strongly depends of charging/discharging frequency and amount	- More expensive then offline UPS - Sensitive to the environment temperature - Life time strongly depends of charging/discharging frequency and amount	- Cost - Generate more heat - Less energy efficient - Sensitive to the environment temperature - Life time strongly depends of charging/discharging frequency and amount

Non-chemical UPS

A number of energy-storage techniques have been developed that store energy in ways other than through chemical reactions, as do batteries.

Flywheel energy storage

A flywheel stores energy in a rotating mass. Stored energy is in proportion to flywheel mass and the square of its rotational velocity, as shown in the following equation:

Equation A3

$$E = \frac{1}{2} * I * \omega^2$$

E is kinetic energy stored in a flywheel
I is moment of inertia
ω is the angular velocity of the flywheel.

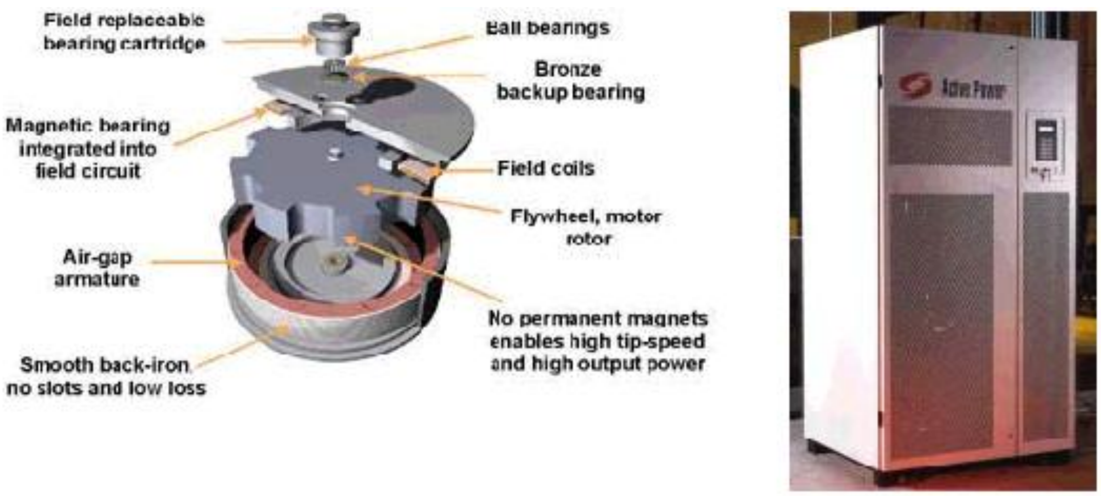

Figure A4 A commercially available flywheel energy storage system [53].

The advantages which make flywheels useful for applications are:

- High power density
- High energy density
- No capacity degradation, the lifetime of the flywheel is almost independent from the depth of the charge and discharge cycle. It can operate equally well on shallow and on deep discharges. Optimizing e.g. battery design for load variations is difficult.
- The state of charge can easily be measured, since it is given by the rotational velocity
- No periodic maintenance is required
- Short recharge time
- Scalable technology and universal localization
- Environmental friendly materials, low environmental impact [54].

Flywheel working principle is that motor spins the rotor to a high velocity to charge the rotor. During the discharge, the motor acts as a generator, converting the kinetic energy into electrical. To ensure the appropriate output voltage and frequency the power electronics are used.

Appendix IV

In this appendix the example of new model tunnel scheme developed in DIgSILENT Power Factory is presented. The Figure A5 shows the load flow analysis of the Model tunnel 1. This scheme is based on the common nowadays tunnel design. However, it includes two wind turbines of 0.5 MW each, two photovoltaic systems (solar panels) located on two sides of the model tunnel, heat extraction and air cleaning system based on the Design 1. The similar scheme is developed for model tunnel with air cleaning system based on Design 2 and current model tunnel with only conventional systems. The scheme is approved by tunnel lead engineer.

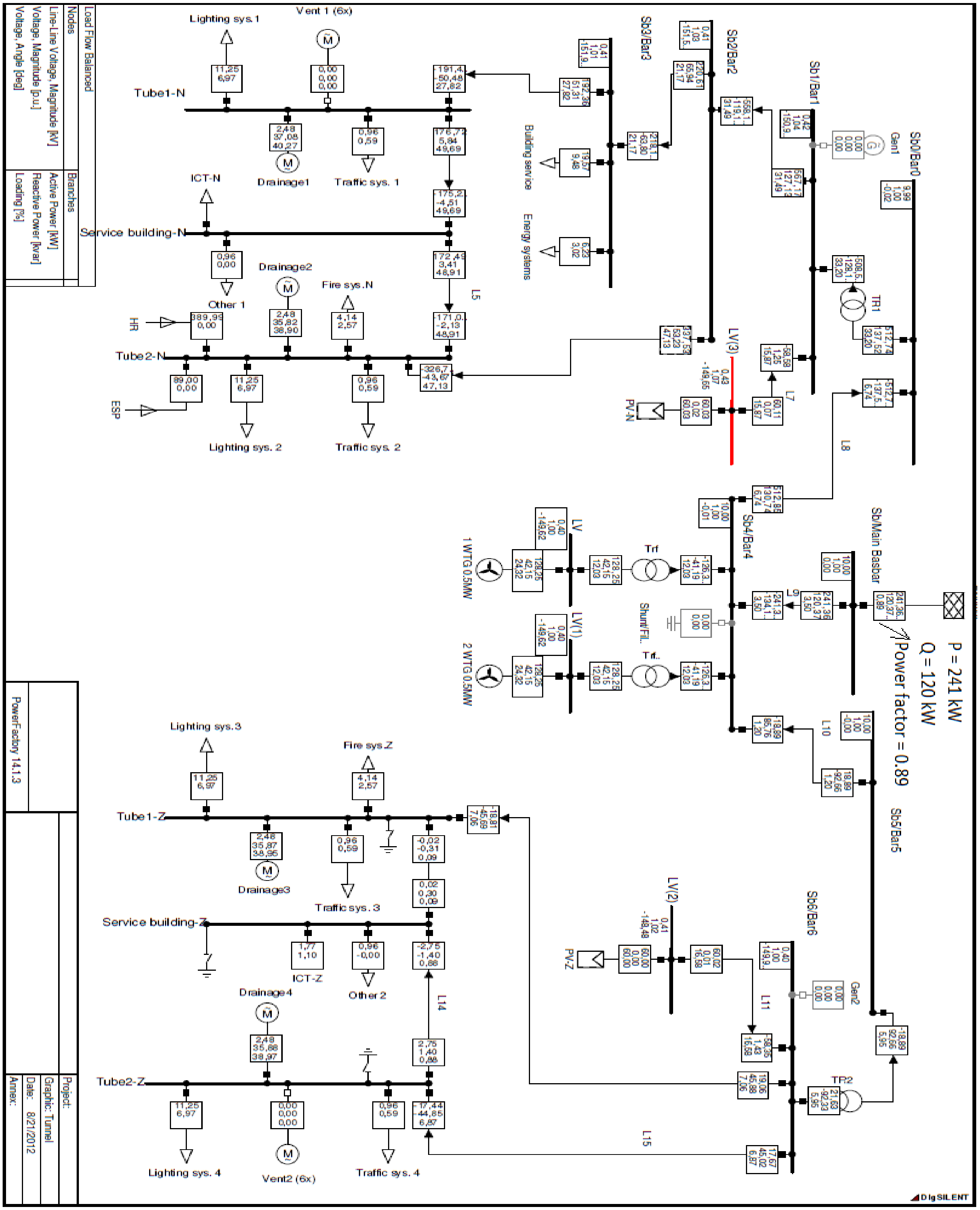

Figure A5 Scheme of Model tunnel 1 in DIgSILENT Power Factory (maximum tunnel load, wind speed 7.5 m/s, irradiation 120 W/m²)

Appendix V

Baseline document

This is the last version of the baseline document that has been written for the course called Project Based Management.

Introduction

Zero Energy Tunnel applies to a general approach for the energy performance in the road tunnels. This study considers the energy consumption associated with the operation of the tunnel services including ventilation, lighting and air cleaning systems and analyses of the possible use of renewable energy and energy storage.

This project study is executed as the final project of the Professional Doctorate in Engineering (PDEng) in Information and Communication Technology, a two years program that is offered by the Stan Ackermans Institute (SAI) at the Eindhoven University of Technology (TU/e). The director of the program is Prof. Dr.-Ing. L.M.F.Kaufmann. The director of KIEN is A. van Duijne. The supervisors of the project are Prof.dr.ir. J.F.G. Cobben and Prof. ir. W.L.Kling, Electrical Energy Systems, TU/e.

The project study results

Problem definition

Zero energy tunnel concept is a good approach to make the road tunnel more energy sustainable and environmental friendly. Furthermore, it is advised to be presented to the governmental organisation, as Rijkswaterstaat.

The developments in this field are based on the next aspects:

- Sustainability
- Health
- Economic issues

Besides of making tunnel a “zero energy” element there is a possibility to generate extra electricity to sale it back to the medium voltage grid. Moreover, this idea is interesting for the tunnel contractors.

Project study deliveries

- To define the framework aspects
- To define system aspects and their design. Within this stage the following systems are considered: tunnel lighting, ventilation, air cleaning and heat extraction systems;
- To develop the new model tunnel concept design that includes the design of its systems and renewable energy sources. Current study does not include the investigation of drainage, traffic installations, fires extinguish, communication and building service systems.

- To prove the model tunnel concept by simulating the electric power flow and the total tunnel energy consumption/generation on yearly basis
- To introduce the possible options of environmental friendly electrical energy storage and uninterruptable power supply technologies, as well as the calculation their basic characteristics to match the model tunnel design requirements.

Delimiters

The topic of zero energy tunnel is quite wide and includes a lot of research on different aspects: economics, civil engineering, electrical engineering. Only after detailed consideration the real implementation can be started. Moreover, the real design should meet all the current requirements according to Rijkswaterstaat and Dutch government. In this study the first concept of Zero Energy Tunnel is developed. The project report does not include:

- Financial estimation for implementation the developed concept
- Maintenance of designed tunnel systems. However, the investigation of their lifetime is presented in the report.
- Safety requirements for the Zero Energy Tunnel concept

Project work strategy (activities)

Definition phase

Tunnel systems:

- Investigation of tunnel design
- Investigation of all subsystem's energy consumption
- Investigation of the background of current requirements
- Interviewing people from RWS and tunnel construction side
- Visiting tunnel constructions
- Defining what can be done to decrease energy consumption

Outcome: Project plan.

Execution phase

Step 1 – Energy consumption reduction:

- Possible way to reduce consumption of lighting system as most energy consuming tunnel systems

Step 2 Design of ventilation system in the model tunnel:

- With visibility control
- With visibility and gas emission control

Step 3 - Emissions estimation inside and outside the tunnel:

- Research about acceptable emission concentration according to different organization
- Estimation the emissions concentration in the tunnel
- Available technology for improving air quality inside and outside the tunnel

Step 4 - New ideas:

- Heat recuperation caused by combustion process in cars' engine
- Estimation the ways for heat utilization

Step 5 – Renewable energy generation (RES):

- Investigation of possible types of RES
- Investigation of how to couple them to the main electricity grid

Step 6 – Energy storage design:

- Choice for type of storage and its capacity estimation

Step 7 – Coupling with the main electricity grid:

- Design bi-directional power flow for several possible scenarios of energy consumption and generation by tunnel construction

Step 8 – Cost estimation:

- Estimation of the payback period and costs for the renewable energy generation

Outcome:

- Estimation of the energy consumption according to investigation in Stages 1,2,3, 4
- Coupling all subsystems between each other
- Estimation of the necessary amount of generated energy by RES

Preparation phase

Step 1 – Tunnel information:

- Obtaining tunnel scheme and investigating the energy consumption statements

Step 2 – Tunnel design study:

- Investigation of all tunnel systems
- Research of new technologies which can be applicable for tunnel construction
- Estimation of energy consumption

Step 3 - Simulation study:

- Study of software
- Design of the electrical scheme of new tunnel construction
- Define different scenarios. These scenarios include several cases:

  Scenario 1: Normal operation without renewable generation in the tunnel
  Scenario 2: Normal operation with renewable generation in the tunnel
  Scenario 3: Short interruptions in the grid

Scenario 4: Long interruptions in the grid. No surplus of generation in the tunnel
Scenario 5: Long interruptions in the grid and surplus of generation in the tunnel

Demands for the Simulation Study:

- Real electricity scheme of a road tunnel
- Tunnel power balances
- Daily and annual load behavior

Finalizing phase

Step 1 – Energy consumption data:

- Preparing data based on the calculation for simulation

Step 2 – Cost estimation

- Getting the market price for the proposed technologies
- Payback period estimation

Step 3 – Preparation for Simulation Study:

- Obtaining the results for different energy consumption scenarios
- Results analysis

Outcome:

Report. The content of the report involves:

- Background of tunnel design and problem definition
- Design of tunnel systems
- Summary of zero energy tunnel design including simulation results
- Conclusion and future work

Control plan

Progress control:

- Monthly meetings with KIEN director
- Weekly meetings with TU/e supervisor

Agenda of monthly meeting:

- Project progress, results
- Risks
- Decision making
- Defining deadlines

Time

	Date
Starting date of the project	15-09-2011
Completing date of the project	31-08-2012
Delivery date for the result	04-07-2012
	Man hours
Capacity – Rimma	40 hours/week
Capacity – TU/e supervisor	1 hour/week
Capacity – KIEN director	1 hour/month

Quality

Requirements for new tunnel design:
- The maintenance should not increase current amount
- The safety requirements should be kept at the current level
- Design should meet the power quality. For this in the detailed design the followings must be done: harmonics analysis, transient phenomena analysis, developing common strategy for different type of the generators (RES, back-up, electrical storage) during the scenarios described in Preparation phase, Step 3.
- The energy consumption should be balanced on the annual base.

Plan:

Phase	What	Who
Definition phase	Collection all information	Rimma
	Estimation what can be done during one year	Rimma, Supervisors TU/e, KIEN
Design phase	Design validation and verification	Rimma + tunnel specialist
Preparation phase	Calculation of energy consumption	Rimma
	Defining RES	
	Developing the electrical scheme	
Realization phase	Simulation analysis	Rimma
Evaluation	Final presentation and report	Supervisors TU/e, KIEN

Information

Phase	Documents, etc.	Recipients
Initial phase	Project assignment	Croon
Definition phase	Project plan	Supervisors + Rimma
Design phase	Tunnel design report	Supervisors
Preparation phase	Tunnel scheme	Supervisor TU/e, tunnel specialists
Realization phase	Simulation results	Supervisor TU/e
	Final Report	Supervisors, Croon, RWS
Along all project	Monthly presentation in power point to illustrate the progress	Supervisor KIEN

Possible risks

- The energy consumption of tunnel with new technology implementation can be higher than the current energy consumption
- The new design cannot meet safety requirements according to Rijkwaterstaat
- The investment cost can be too high and payback period can be more than 25 years.

Money

Financial attractiveness

It is very difficult to estimate the overall financial attractiveness of the whole system. There are many important technical issues related to the underground construction and operation issues. Thus, the overall investment and benefits is not covered by this research.

Possible earnings

In case the current project will cause interest of Rijkswaterstaat and other tunnels contractors, KIEN would get the investment money back. One of the ways to make Rijkswaterstaat be interested in the "Zero Energy Tunnel" concept is to make it well-known for society. The awareness of the society about the impact of the traffic via tunnels on surrounding environment can speed up the process of accepting the new tunnel design.

Project costs

The current research expenses:

- Salary of PDEng trainee (author of this report) and people involved in this project as supervisors and consultants
- The costs of equipment used during the study
- DIgSILENT Power Factory software

- DIgSILENT Power Factory training (€ 1500)
- Overall costs for one PDEng trainee (€ 210 000 for two years).

Organization

- Project owner: KIEN, director A. van Duijne
- Project leader: Rimma Dzhusupova, M.Sc.
- TU/e Supervisors: Prof. dr.ir. J.F.G. Cobben, Prof.ir. W.L. Kling
- Director of SAI-ICT program: Prof. Dr.-Ing. L.M.F. Kaufmann

Third parties:

  - Rijkswaterstaat
  - Tunnel contractors

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