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Viability study for the development of prototypes with innovative technology

Forfatter
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Emneord
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Sammendrag
Denne rapporten er den femte av totalt seks rapporter fra et to-årige FoU-samarbeid Varige konstruksjoner har med det spanske engineering-selskapet Geocontrol. Samarbeidet er rettet mot utvikling av energieffektive tunneler gjennom prosjektet ENERTUN som Geocontrol leder. ENERTUN gjennomføres i regi av EEA GRANTS, en samarbeidsorganisasjon der EØS-landene Norge, Island og Lichtenstein gir midler og tilskudd (via Innovasjon Norge) til 16 EU-land i Sentral- og Sør-Europa.

Rapporten gir en oversikt over nytte/kost vurderinger og levedyktighet for ulike tiltak av energiøkonomisering i tunneler.

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Energy efficiency in tunnels- ENERTUN - D4.1

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Summary
This report is the fifth of a total of six reports from a two-year R&D collaboration Durable structures have with the Spanish engineering company Geocontrol. The partnership is aimed at developing energy efficient tunnels through the project ENERTUN as Geocontrol leads. ENERTUN is pursued by the EEA GRANTS, a cooperative organization where the EEA countries Norway, Iceland and Lichtenstein provides funds and grants (via Innovation Norway) for 16 EU countries in Central and Southern Europe.

The report provides an overview of the cost / benefit assessments and viability of various measures of energy conservation in tunnels.

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Forord

Denne rapporten inngår i en serie rapporter fra **etatsprogrammet Varige konstruksjoner**. Programmet hører til under Trafikksikkerhet-, miljø- og teknologiavdelingen i Statens vegvesen, Vegdirektoratet, og foregår i perioden 2012-2015. Hensikten med programmet er å legge til rette for at riktige materialer og produkter brukes på riktig måte i Statens vegvesen sine konstruksjoner, med hovedvekt på bruer og tunneler.

Formålet med programmet er å bidra til mer forutsigbarhet i drift- og vedlikeholdsfasen for konstruksjonene. Dette vil igjen føre til lavere kostnader. Programmet vil også bidra til å øke bevisstheten og kunnskapen om materialer og løsninger, både i Statens vegvesen og i bransjen for øvrig.

For å realisere dette formålet skal programmet bidra til at aktuelle håndbøker i Statens vegvesen oppdateres med tanke på riktig bruk av materialer, sørge for økt kunnskap om miljøpåkjenninger og nedbrytningsmekanismer for bruer og tunneler, og gi konkrete forslag til valg av materialer og løsninger for bruer og tunneler.

Varige konstruksjoner består, i tillegg til et overordnet implementeringsprosjekt, av fire prosjekter:

Prosjekt 1: Tilstandsutvikling bruer
Prosjekt 2: Tilstandsutvikling tunneler
Prosjekt 3: Fremtidens bruer
Prosjekt 4: Fremtidens tunneler

Varige konstruksjoner ledes av Synnøve A. Myren. Mer informasjon om prosjektet finnes på vegvesen.no/varigekonstruksjoner

Denne rapporten tilhører **Prosjekt 4: Fremtidens tunneler** som ledes av Harald Buvik. Prosjektet skal bidra til at fremtidige tunneler bygges med materialer, utførelse og kontroll bedre tilpasset det miljøet konstruksjonene er utsatt for. Prosjektet skal bygge videre på arbeidet i Moderne Vegtunneler, samt innspill fra Prosjekt 2: Tilstandsutvikling tunneler, med hovedfokus på tunnelkonstruksjonen i et levetidsperspektiv. Prosjektet skal resultere i at installasjoner i fremtidige tunneler oppnår tiltenkt levetid med reduserte og mer forutsigbare drift- og vedlikeholdskostnader.

Rapporten er utarbeidet av *Luis Miguel Gonzalo, Geocontrol*.

EFICIENCIA ENERGÉTICA EN TÚNELES
ENERTUN
ENERGY EFFICIENCY IN TUNNELS

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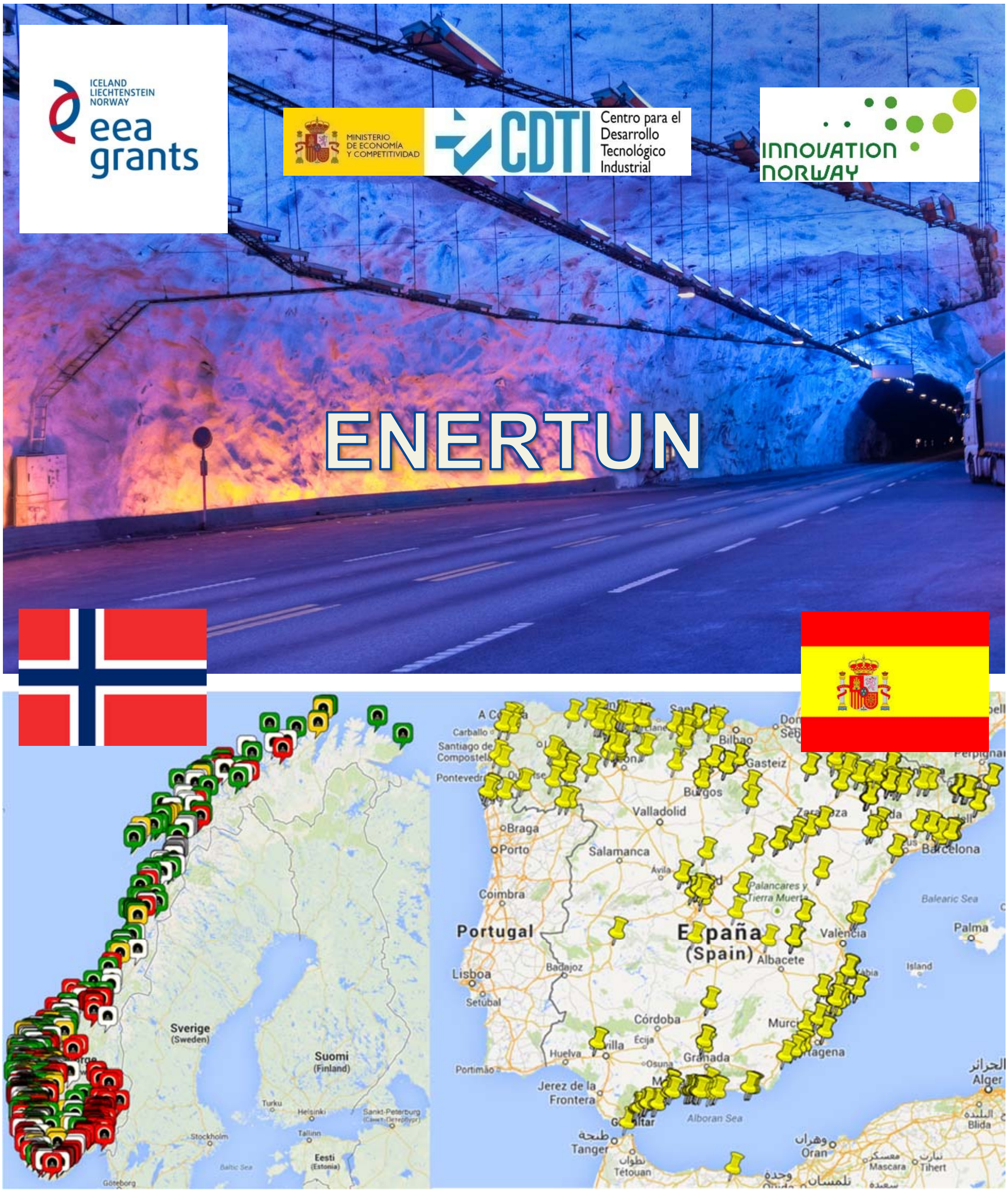

DELIVERABLE 4.1.- VIABILITY STUDY FOR THE DEVELOPMENT OF PROTOTYPES WITH INNOVATIVE TECHNOLOGY IN ROAD TUNNELS

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ENERTUN
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ENERTUN
DELIVERABLE 4.1.- VIABILITY STUDY FOR THE DEVELOPMENT OF PROTOTYPES WITH INNOVATIVE TECHNOLOGY IN ROAD TUNNELS

1. INTRODUCTION

In previous stages of the Enertun project, it has been studied and analysed the preponderance of the different sources of energy consumption.

As part of the WP4, in this document it is assessed the economic viability of the implementation of the efficiency – oriented measures that have arisen through the WP1 and recommended in WP3. The assessment is done following this sequence:

- Determination of the investment cost and estimation of the lifetime of the measure being studied.
- Determination of the cash flows that, in this case, is the difference of energetic costs between the former and the new installation. The cash flows must be corrected by a inflation rate in order to take into account the variation in time of the money's value.
- Determination of the investment economic parameters.

Due to the wide range of possible configurations for tunnels, in order to facilitate the viability analysis of the measures, available data have been used, related to a tunnel chosen among those considered as more adequate for every measure.

In this document it is analysed the viability of 9 efficiency - related measures:

- Wireless tunnel.
- Continuous lighting control.
- On – off lighting control.
- System for the profitability of the external lighting.
- Real time database.

- Computational consumption modelling.
- Hydraulic turbines.
- Micro wind generators.
- Asphalt piezo electric generator.

2. WIRELESS TUNNEL

Currently, our society is immersed in what is called the wireless communications technological revolution.

One of the main advantages of this technology is the mobility, with no need of any wire. The fact that the inlet point to the network is not related to a fixed location and that the transmission mean is already prepared to allow its spreading, which can be faster than any other technology.

In a computer network we can differentiate four important elements that intervene in its definition:

1) The communication protocol defines the language and the group of rules that facilitates the communication between the emitter and the receptor, with the aim of them being able to exchange information. There are many protocols but the most common nowadays is TCP/IP (Transport Control Protocol / Internet Protocol).
2) The topology defines the inter connexion among the communication nodes. The most common network topologies are bus topology, star topology, ring topology or point to point topology.
3) The security is the element that allows to guarantee confidentiality, authentication and data integrity.
4) The transmission mean is the element that differentiates more clearly the communication technologies with wire with respect to the wireless ones. This is the mean where the signal with the data travels.

Currently, communications that take place through a wire (guided) use different means of transmission, such as twisted pair cables (UTP or STP), coaxial cable, optical fibre or high voltage cables.

The mean of transmission for wireless communications (not guided) is the electromagnetic spectrum that is colloquially called air.

The electromagnetic spectrum

The electromagnetic spectrum is the range of frequencies of all the electromagnetic waves that can spread through the free space, classified according to their wavelength and their frequency.

As their name indicates, these waves have a magnetic component part and an electric component part.

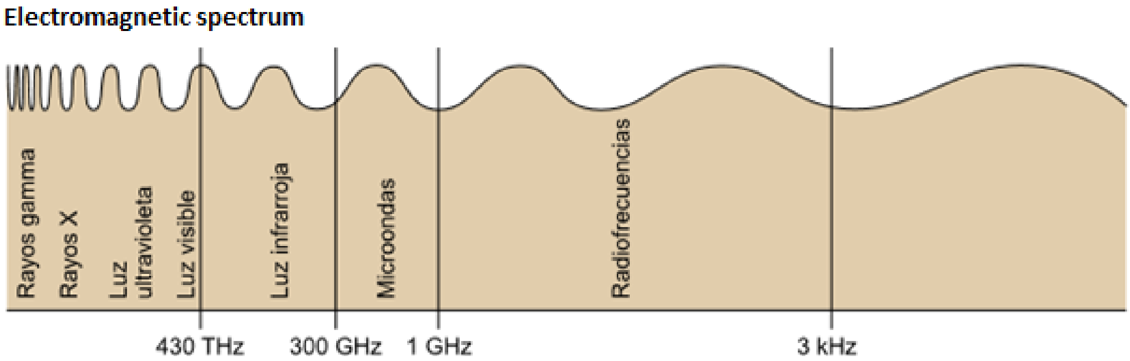

Figure 2.I. Electromagnetic spectrum.
(Source: Fundació per a la Universitat Oberta de Catalunya).

The most used wave ranges in the wireless domain are the following:

- Infrared (IR): they are used in point-to-point communication of short range, they can be easily directed and cannot avoid obstacles. This mean is employed usually in the TV remote control and till several years it was a communication system widely used to connect devices closed to each other.
- Microwaves (MW): This range of frequencies is adequate for far – reaching transmissions (satellite communications, point – to – point ground communications as an alternative to coaxial cable or optical fibre and also most of the wireless technologies that exist currently, such as UMTS, Bluetooth or WLAN). Microwaves let usually to be oriented and use a part of the mirror with frequencies lower than infrared.
- Radio frequencies (RF): This is the range used by the radio transmissions (FM, AM) and terrestrial digital television (TDT). The radio frequencies are Omni directional and can pass through obstacles without any problem.

2.1. WIRELESS COMMUNICATIONS

In a wide and general sense, it is understood wireless communications those between devices (mobile or not) or between people that exchange information using the electromagnetic spectrum.

Classification

Depending on the information that is consulted, it can be found different classifications of the wireless communications. In this report, they will be classified according to their reaching distance and their way of controlling the access to the network.

Depending on the reaching distance, it is possible to establish three groups:

- Wireless Personal Area Networks (WPAN).
- Wireless Local Area Networks (WLAN).
- Wireless Wide Area Networks (WWAN). It is possible to differentiate two kinds of WWAN, depending on who controls its access:
  - Fixed communication (FWWAN: Fixed Wireless Wide Area Networks).
  - Mobile communication (MWWAN: Mobile Wireless Wide Area Networks).

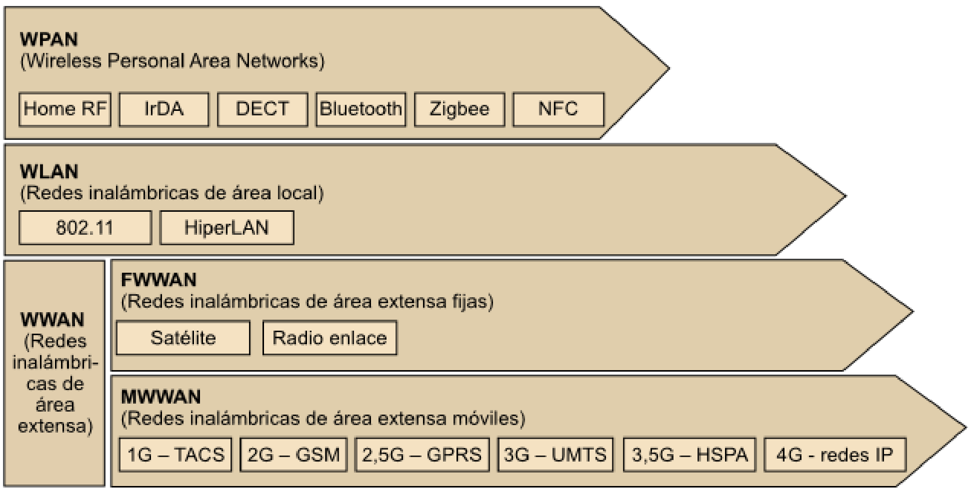

Figure 2.1.I. Wireless Communications Classification.
(Source: Fuente: Fundació per a la Universitat Oberta de Catalunya).

2.1.1. WIRELESS PERSONAL NETWORKS (WPAN)

The WPAN have a severe limitation of reaching distance: the devices communicating with each other must be quite close.

The most used technologies of WPAN are: Buletooth, DECT (Digital Enhanced Cordless Telecommunications), Irda (Infrared Data Association), NFC (Near Field Communication) and Zigbee.

2.1.1.1. Bluetooth

Bluetooth is a specification regulated by the wort team IEEE 802.15.1, which allows the transmission of voice and data between different devices through a connexion of radio frequency in the range ISM of 2,4 GHz.

Bluetooth allows to connect different wireless electronic devices, such as the Personal Digital Assistant (PDA), mobile phones, laptops, etc., which makes easier and cheaper the interoperability among different manufacturers.

Bluetooth define a short reaching connexion, from 10m to 100m (average).

In a Bluetooth network, any device can operate as the master or the slave:

- The Master device is in charge of defining how to establish communication physically (frequency, phase, etc).
- The Slave devices coordinate their transmissions depending on the specifications of the Master. Usually, the first that asks for the service is the one that plays the role of Master, unless the network is already established.

2.1.1.2. DECT

The digital technology DECT (Digital Enhanced Cordless Telecommunications) appears as a response to the need of the analogical phone communications at the beginning of the eighty's to evolve to a digital context. The wireless digital transmission offers several advantages with respect to the analogical one: fewer interferences, more capacity of devices in the same zone, more security (data can be encrypted) and more mobility (some mechanisms can be established to pass from a network to another one, which is called roaming).

The DECT standard appears officially in the beginning of 1988, fuelled by the ETSI. Initially, it was focused on the definition of the radio connexion between wireless devices and fixed stations and also on the necessary protocols and standards to develop transmission functions (handover) among BTS (Base Transmission Stations).

The DECT standard, which originally admitted data frequencies till 552 Kbps, has evolved to allow transfers of even 2 Mbps.

The devices that use this technology usually operate in a 50m range.

2.1.1.3. IRDA

The Infrared Data Association is an association that integrates more than 160 companies. The standard IrDA uses the infrared frequency spectrum to transfer information.

The use of the IrDA technology has spread extensively, over all during the ninety's and at the beginning of the 21st century, thanks to its low implementation cost and low battery consumption. In addition, it is quite flexible and able to adapt to a large amount of applications and devices, such as Personal Digital Assistants (PDA), telephones, printers and laptops.

The devices that use the IrDA communicate with each other through the use of the LED diode (Light Emitting Diode). It is necessary for these devices to be aligned all with each other. The maximum allowable deviation is 30º.

It allows the bidirectional communication between two extremities at speeds that oscillate between 9600 bit/s and 4 Mbit/s.

The communication range is excessively reduced, up to 1m.

2.1.1.4. NFC

The technology Near Field Communication (NFC) allows the data transmission in a different way between different devices through a radio frequency in the ISM band of 13,56 MHz.

The connection is produced when two devices NFC are quite close to each other (less than 20cm).

The NFC technology is an extension of the standard ISO/IEC-14443 for proximity cards without contact that combines the interface of an intelligent card and a reader in a single device, which makes it compatible with all the pay infrastructure without a contact that exists currently but not applied to the tunnels domain.

2.1.1.5. Zigbee

Zigbee is a standard for Wireless communications, regulated by the workteam IEEE 802.15.4 in 2004, which allows to enable wireless networks with control capacities and monitor that are secure, with low energy consumption and low cost processing, bi directionally.

Zigbee is promoted by Zigbee Alliance, an international community of more than 100 companies, such as Motorola, Mitsubishi, Philips, Samsung, Honeywell and Siemens, among others. In fact, Zigbee is not a technology, but a standardised group of solutions that can be implemented by any manufacturer.

Zigbee uses the ISM band for industrial, scientific and medical purposes; more specifically, 868 MHZ in Europe, 915 in USA and 2,4 GHz all around the world. However, when it comes to designing devices, the manufacturers will choose always the 2,4 GHz band, as it is free all over the world.

A Zigbee network can have a maximum of 65535 nodes, distributed in sub networks of 255 nodes, with a low electric consumption.

Its speed is up to 250 kbit/s, which isn't enough for transmissions with a high load of information, as it is the case of the tunnels.

The transmission ranges oscillate between 10 and 75m, although it depends mostly of the environment.

2.1.2. WIRELESS LOCAL NETWORKS (WLAN)

A WLAN is a network of limited geographic coverage, relatively high transmission velocity, low error levels and managed privately and that communicates basically through microwaves.

The WLAN are an extension and/or an alternative to the LAN that are wired. The WLAN's users can access to the resources offered by a LAN without the dependence of a wired network infrastructure (cables, connectors, etc).

The characteristics of the WLAN networks are:

- Mobility: the WLAN users can access the information in real time from anywhere from the organisation.

- Simple installation: there is no need to worry about the cables installation in the coverage ratio.

- Flexibility: it allows to access places that a wired LAN would never reach.

- Low cost: although the initial cost of the WLAN infrastructure can be higher than in the case of a wired LAN, in long term, it can mean savings in places with frequent changes of devices placements (a road tunnel network is not the case).

- Scalability: the WLAN can be configured with different topologies in an easy way depending on the environment's need. It is possible to find ad hoc WLAN (where the devices can enter the network successively) and the WLAN with access points connected to the main network.

Despite the previously mentioned advantages, the WLAN have several limitations and requirements, such as:

- Velocity: the WLAN must be able to transmit information at a speed of the same order of the LAN (more than 500 Mbps).

- Delays: they are relevant in any application, but especially in wireless transmissions.

- Complicated accesses: in the inside of a building it is possible to find factors that soften the signal. A mobile device can receive much less power than another one.

- Consumption: the mobile devices are usually electrically fed with batteries; therefore, they must be designed so that they'll have an efficient consumption (sleep mode, low consumption mode, low consumption in the sending of packets, etc).

- Maximum number of nodes and maximum coverage: a WLAN may assume hundreds of nodes. The typical area for a WLAN is 10-100 m2, which means spreading delays lower than 1.000 nanoseconds.

- Security: the mean in which the information is transferred (electromagnetic waves) is open to anyone in the coverage area. In order to guarantee the security, encryption algorithms are used.

- Interferences: they can be produced because of two simultaneous transfers (collisions) or two emitters using the same frequency band. The collisions also are produced when several stations waiting for the channel to be free start transmissions at the same time. Unlike the local wired networks, in the WLAN an effect of an unseen node is produced, which means an increase of collisions.

The most used technologies of WLAN are mainly the different alternatives of IEEE 802.11, although there are others, like the HIPERLAN.

2.1.2.1. IEEE 802.11

The IEEE 802.11 is a family of standards for wireless local networks developed by the IEEE, which was defined in 1997 (in 1999 the standards 802.11a and 802.11b were defined). The standard guarantees the interoperability among different manufacturers. That is, as an example, that a WLAN card for PC from a manufacturer can operate with an access point from another manufacturer.

The standard 802.11 describes the functionality of the layers and sublayers and the relationships among them, but it doesn't specify the way they must be done; it only indicates how the equipment must behave and gives autonomy to the manufacturer about the way of implementing it.

The main aim of the standard 802.11 is to guarantee the functionality of the applications without having to consider whether the communication is wired or not.

The standard 802.11 is a family of specifications, among which the following ones can be highlighted:

- IEEE 02.11a: it allows velocities up to 54 Mbps and use the band of frequencies of 5 GHz. This protocol is oriented to the transmissions of packets, but doesn't provide functions of quality of service.

- IEEE 802.11b (initially called Wi-Fi): it allows velocities up to 11 Mbps and uses the band of frequencies of 2,4 GHz.

- IEEE 802.11g: it allows velocities of up to 54 Mbps. It is an evolution of the IEEE 802.11b and uses the same band of frequencies of 2,4 GHz.

- IEEE 802.11i: it was created to overcome the vulnerability of the security for authentication and codification protocols. This standard includes the protocols 802.1x, TKIP and AES and it is implemented with WPA2.

- IEEE 802.11n: it allows velocities of up to 600 Mbps and can work on two band of frequencies: 2,4 GHz (the one used by 802.11b and 802.11g) and 5 GHz (the one used by 802.11a). 802.11n is compatible with devices based on all the previous specifications before 802.11. The fact of working on the band of 5 GHz allows it to reach a higher efficiency, since it is less congested.

2.1.2.2. HiperRLAN

The High Performance Radio Local Area Network (HiperLAN) is a standard for Wireless local networks developed by the ETSI.

The first version of this standard, HiperLAN1 (HiperLAN Type 1), appeared in 1996 and allowed velocities up to 20 Mbps. The evolution of this standard, which appeared in 2000, is named as HiperLAN2 (HiperLAN Type 2) and allows velocities up to 54 Mbps. Both standards operate in the band of frequencies of 5 GHz.

2.1.3. WIRELESS WIDE – RANGING NETWORKS (WWAN)

The WWAN allow the network connection of networks and users from zones remote from each other. It is possible to differentiate two types:

- Fixed WWAN, which use satellite of radio connection.

- Mobile WWAN, which use the companies or other public services in the transmission and reception of the signals.

2.1.3.1. Fixed WWAN (FWWAN)

The WWAN networks can use two technologies:

- Radio connection: using radio connections it is possible to connect networks that are geographically far from each other, with different bands of the electromagnetic spectrum (infrared, microwaves, laser, etc), which can be point-to-point or point to multipoint.

- Satellite: communications by satellite cover a big surface of the Earth, they have a high bandwidth and the cost of transmission doesn't depend on the distance; however, they have the disadvantage of the delays in the propagation of the signal.

2.1.3.2. Mobile WWAN (MWWAN)

In the MWWAN networks, the terminal that sends and receives information is moving. In these networks there are usually many users connected simultaneously (multiple access) that use the services.

Currently in Europe, there are different technologies of MWWAN, classified by generations, where the ones to highlight are the following five:

1) 2G (second generation). Second generation technology, used to describe digital mobile networks, like the GSM, which replaced the first generation mobile networks.
   - GSM. The Group Special Mobile was the organisation in charge of the technical configuration of a standard for transmission and reception for mobile telephony. In Europe, the used bands of frequency ISM are 900 MHz and 1800 MHz. This technology appeared in 1990 with a velocity of transmission of 9,6 Kbps. GSM operates through the communication of circuits; this means that there is a phase of establishment for the connection, which adds a delay time and assures that the call will always be open, although there is no data transmission, while the connection is not closed.

2) 2.5G (second and medium generation). It is considered an intermediate technology between 2,5G and 3G and it is based on the technological updates of the GSM mobile networks to increase the data transmission velocity and its efficiency. This generation includes the systems GPRS and EDGE:
   - GPRS. It is a packets commutation technique that started to be used in 2001 and that was integrated with the current GSM networks infrastructure. This technology allows a data velocity of 56-115 Kbps. Its advantages are numerous and it is applied to data transmission that require discontinuous traffic, such as internet and electronic messaging (SMS and MMS). With this technology, it disappears the concept of connection delay and former concepts like circuits commutation are replaced by packets commutation. The mobile telephony service providers will now be able to charge the data packets that are really sent and received. The band width will be able to be delivered following the client's needs, depending on the communication needs.

- o EDGE. It is also known as EGPRS (Enhanced GPRS) and it is a technology that appeared in 2003, considered as an evolution of GPRS. EDGE provides a bandwidth which is higher than the GPRS', between 236 and 384 Kbps, which allows executing applications that require a higher data transfer velocity, like the video or other multimedia services.

3) 3G (third generation). 3G technologies are the answer to the specification IMT-2000 of the International Telecommunications Union (ITU) to have bandwidth in the mobile telephony and transmit an important data volume with the network. Thanks to the third generation, many services will be available: video conferences, video downloading, watching TV in real time and the possibility of doing most of the tasks from the mobile device. This generation includes the UMTS system:

   - o UMTS (Universal Mobile Telecommunications System). The UMTS standard is based on the WCDMA technology. UMTS is managed by the 3GPP organisation (version 4), also responsible for GSM, GPRS and EDGE. UMTS was first commercialised in 2005 and its maximum data transmission velocity 1,92 Mbps.

4) 3,5G (third and medium generation). As it happens with 2,5G, 3,5 is considered an intermediate technology between 3G and 4G, with the main aim of increasing considerably the data transmission velocity because of the current customers' needs. It is, thus, the evolution of 3G and the previous step of the fourth generation 4G. This generation includes the systems HSPA and HSDPA:

   - o HSPA (High Speed Packet Access). It is a combination of technologies, both subsequent and complementary to 3G, such as HSDPA or HSUPA. Theoretically, it allows velocities up to 14,4 Mbps (down) and 2 Mbps (up), depending on the state or the saturation of the network and its implantation.

   - o HSDPA (High Speed Downlink Packet Access). It is the optimisation of the spectral technology UMTS/WCDMA, included in the specifications of 3GPP (version 5) and consists of a new channel shared in the downlink connection that improves significantly the maximum capacity for the information transmission, reaching transmission rates of 14,4 Mbps and an average of 1 Mbps. It is completely compatible with UMTS and most of the UMTS providers allow the use of this technology.

5) 4G (fourth generation). The WWRF defines 4G as a network integration that operates with the internet technology where the whole network is IP, combining it with another uses such as WiFi and WiMAX. Currently, 4G is not a well-defined technology or standard, but a collection of technologies and protocols that allow the maximum efficiency with a cheaper wireless network. 4G includes wireless techniques of high efficiency, such as MIMO and for the radio access, the former access type characteristic of UMTS (3G) is replaced by the OFDMA in order to optimise the access. This generation includes the systems LTE and WiMAX.

- o LTE (Long Term Evolution). This is the standard of 3GPP (version 8, 9 and 10) defined as an evolution of the 3GPP UMTS (3G) and a new concept of evolutionary architecture (4G). LTE is the key factor for the take-off of the mobile internet, since it makes possible the data transmission at a velocity higher than 300 Mbps in movement, which allows video transmissions or HD television.

- o WiMAX (Worldwide Interoperability For Microwave Access). It is a technology, between WLAN and WWLAN, which allows making connections at high distances, with big bandwidths and not needing a straight line between them with no obstacles. WiMAX verifies the standards IEEE 802.16 and it is compatible with other standards such as the IEE 802.11, to establish telecommunications systems combinedly.

- o WIMAX (Worldwide Interoperability For Microwave Access). Es una tecnología, entre WLAN y WWLAN, que permite hacer conexiones a grandes distancias, con grandes anchos de banda y sin necesitar línea de visión directa entre antenas. WiMAX cumple los estándares IEEE 802.16 y es compatible con otros estándares, como el IEE 802.11, para establecer sistemas de telecomunicaciones conjuntos.

2.2. BEST CHOICE FOR THE WIRELESS TUNNEL

As it has been verified in the previous section, the number of choices for wireless communications is quite numerous. The far – reaching communications networks are ruled out, since they're not adequate for the specific case of a road tunnel. In addition, this kind of networks usually need some licences that are quite difficult to obtain.

On the opposite, the wireless personal networks don't cover the average distance of a road tunnel; thus they are ruled out as well. There is an exception with the Zigbee network, since although it is a short – reaching network, it allows far – reaching communications thanks to the creation of a mesh of networks.

The wireless local networks are adequate as far as distance and number of nodes is concerned, but make appear additional relevant consumptions; thus, it should only be appropriate for installations with just a few nodes.

Once the different possibilities have been analysed, the best choice is based on the combination of two technologies:

- ◈ WiFi network, with a considerable consumption, for a rapid communication among a few devices.

- ◈ Zigbee network, with a low consumption, for a slow communication among numerous devices.

2.3. CALCULATION OF THE INVESTMENT COST

The implementation of a wireless communication has the main economic advantage of savings related to the communication cables. This advantage only has sense in new installations, as in existing ones the removal of the existing cables may be a cost instead of a saving.

In the Folgoso Tunnel, under the assumption that it is a tunnel of new construction, the changes related to the implementation of a wireless communication would be:

- Installation of fluorescent ballasts in the permanent lighting system with Zigbee communication. Then it shouldn't be necessary any communication cable, nor the control equipment for the DALI application.

- Installation of switches with WiFi communication in the PA system units. Then, the optical fibre shouldn't be necessary among them.

- Installation of switches with WiFi communication in the Variable Messaging Pannels (VMP). Then, it shouldn't be necessary any communication cable.

The investment cost is incremental, comparing the cost related to installing equipment with wireless communication with the cost of communication based on cables or optical fibre.

INVESTMENT COST				
Concept	**Unit**	**Measure**	**Unitary Price (€/ud)**	**Total price (€)**
Zigbee ballasts	unit	2200	8,55	18.810,00
DALI cables	m	-12000	1,27	-15.240,00
DALI control equipment	unit	-18	250,44	-4.507,92
WiFi switches in PA system	unit	33	45,89	1.514,37
Optical fibre	m	-9000	1,50	-13.500,00
WiFi switches in VMP	unit	26	87,99	2.287,74
Twisted pair cables	unit	-1950	1,29	-2.515,50
			TOTAL	-10.635,81 €

Table 2.3.I. Investment cost.

In this case the initial investment is negative, which means that the installation cost for the wireless tunnel is less expensive than in the case of the wired tunnel.

2.4. CALCULATION OF THE CASH FLOWS

In order to calculate the cash flows of the investment, it is necessary to take into account the amount of energy that the system consumes throughout the years under operation and multiply it by the price in kWh during this time period.

2.4.1. ENERGY CONSUMPTION INCREASE

With the exception of the elimination of the DALI control equipment, the wireless tunnels has a higher electric consumption.

ELECTRIC CONSUMPTION			
Concept	**Measure**	**Consumption [W/Ud]**	**Consumption [W]**
Zigbee ballasts	2200	1,50	3.300,00
DALI control equipment	-18	5,00	-90,00
WiFi switches in PA system	33	7,50	247,50
WiFi switches in VMP	26	5,50	143,00
		TOTAL	3.600,50

Table 2.4.1.I. Increase of the electric consumption.

This electric consumption impacts directly on negative cash flows. In order to calculate these cash flows it is necessary to estimate the energy price in the forthcoming years.

2.4.2. ENERGY COST ESTIMATION

In order to estimate the energy price in the forthcoming years, a study concerning the variation of the price of the kWh throughout the last years has been done, as it is shown in the following table.

Prices of the electric fare -ATR 2.0 A-, in the last 5 years						
Year	**Date for change in fare**	**Price**		**Increase**		
		Power (€/day)	**Energy (€/kWh)**	**Power increase**	**Energy increase**	
2007	01/01/2007	0,05272957	0,089868			
	01/07/2007	0,05272957	0,089868			
2008	01/01/2008	0,05446963	0,092834	3,30%	3,30%	1,65%
	01/07/2008	0,05446963	0,092834	0,00%	0,00%	
2009	01/01/2009	0,05474517	0,11248	0,50%	21,20%	11,60%
	01/07/2009	0,056529	0,11473	3,30%	2,00%	
2010	01/01/2010	0,056529	0,117759	0,00%	2,60%	4,45%
	01/10/2010	0,056529	0,125159	0,00%	6,30%	
2011	01/01/2011	0,056529	0,140069	0,00%	11,90%	6,75%
	01/07/2011	0,056529	0,142319	0,00%	1,60%	
	01/10/2011	0,056529	0,152559	0,00%	7,20%	
2012	01/01/2012	0,07447327	0,168075	31,74%	10,17%	-0,54%
	01/04/2012	0,05998134	0,142138	-19,46%	-15,43%	
	01/06/2012	0,05998134	0,142208	0,00%	0,05%	
	01/07/2012	0,05998134	0,149198	0,00%	4,92%	
	01/10/2012	0,05998134	0,145578	0,00%	-2,43%	
2013	01/01/2013	0,05998134	0,150938	0,00%	3,68%	-1,95%
	01/04/2013	0,05998134	0,138658	0,00%	-8,14%	
	01/07/2013	0,05998134	0,140728	0,00%	1,49%	
	01/08/2013	0,09766979	0,124985	62,83%	-11,19%	
	01/10/2013	0,09766979	0,130485	0,00%	4,40%	
2014	01/01/2014	0,09766979	0,133295	0,00%	2,15%	-2,37%
	01/02/2014	0,11518747	0,124107	17,94%	-6,89%	
Year	**Date for change in fare**	**Power (€/day)**	**Energy (€/kWh)**	**Power increase**	**Energy increase**	**2,80%**
		Price		**Increase**		**Annual average increase of the energy price**

Table 2.4.2.I. Estimation of the increase of the anual energy Price.

This way, it is foreseen an increase of 2,8% in the price of the kWh throughout the entire lifetime of the system.

The value of the kWh for the month of September in 2015 for the particular case of Iberdrola, one of the most representative electric companies in Spain is 0,1217583 €/kWh; thus, taking as a reference this price, the theoretical prices for the kWh in the forthcoming years can be calculated.

This increase will be maintained for all the viability studies in the present report.

2.4.3. INFLATION ESTIMATION

When it comes to establish the cash flows, it must be applied an inflation rate to take into consideration the variation of the money's value throughout the time.

In order to calculate the inflation, the data concerning the IPC (Index for the Price of the Consumption) have been extracted from the INE (National Statistics Institute) throughout the last years:

	Annual variation	Annual average
2015M09	-0,9	
2015M08	-0,4	
2015M07	0,1	
2015M06	0,1	
2015M05	-0,2	-0,6
2015M04	-0,6	
2015M03	-0,7	
2015M02	-1,1	
2015M01	-1,3	
2014M12	-1,0	
2014M11	-0,4	
2014M10	-0,1	
2014M09	-0,2	
2014M08	-0,5	-0,2
2014M07	-0,3	
2014M06	0,1	
2014M05	0,2	
2014M04	0,4	
2014M03	-0,1	0,5

	Annual variation	Annual average
2014M02	0,0	
2014M01	0,2	
2013M12	0,3	
2013M11	0,2	
2013M10	-0,1	
2013M09	0,3	
2013M08	1,5	
2013M07	1,8	
2013M06	2,1	
2013M05	1,7	
2013M04	1,4	
2013M03	2,4	
2013M02	2,8	2,5
2013M01	2,7	
2012M12	2,9	
2012M11	2,9	
2012M10	3,5	
2012M09	3,4	2,2
2012M08	2,7	

	Annual variation	Annual average
2012M07	2,2	
2012M06	1,9	
2012M05	1,9	
2012M04	2,1	
2012M03	1,9	
2012M02	2,0	
2012M01	2,0	
2011M12	2,4	
2011M11	2,9	
2011M10	3,0	
2011M09	3,1	
2011M08	3,0	3,1
2011M07	3,1	
2011M06	3,2	
2011M05	3,5	
2011M04	3,8	
2011M03	3,6	
2011M02	3,6	2,7
2011M01	3,3	

	Annual variation	Annual average
2010M12	3,0	
2010M11	2,3	
2010M10	2,3	
2010M09	2,1	
2010M08	1,8	
2010M07	1,9	
2010M06	1,5	
2010M05	1,8	
2010M04	1,5	
2010M03	1,4	
2010M02	0,8	0,9
2010M01	1,0	
2009M12	0,8	
2009M11	0,3	
2009M10	-0,7	
2009M09	-1,0	
2009M08	-0,8	
2009M07	-1,4	
2009M06	-1,0	
2009M05	-0,9	-0,4
2009M04	-0,2	
2009M03	-0,1	
2009M02	0,7	
2009M01	0,8	
2008M12	1,4	
2008M11	2,4	
2008M10	3,6	
2008M09	4,5	
2008M08	4,9	4,0
2008M07	5,3	
2008M06	5,0	
2008M05	4,6	
2008M04	4,2	
2008M03	4,5	
2008M02	4,4	
2008M01	4,3	3,6
2007M12	4,2	
2007M11	4,1	

	Annual variation	Annual average
2007M10	3,6	
2007M09	2,7	
2007M08	2,2	
2007M07	2,2	
2007M06	2,4	
2007M05	2,3	
2007M04	2,4	
2007M03	2,5	
2007M02	2,4	2,5
2007M01	2,4	
2006M12	2,7	
2006M11	2,6	
2006M10	2,5	
2006M09	2,9	
2006M08	3,7	
2006M07	4,0	
2006M06	3,9	
2006M05	4,0	3,8
2006M04	3,9	
2006M03	3,9	
2006M02	4,0	
2006M01	4,2	
2005M12	3,7	
2005M11	3,4	
2005M10	3,5	
2005M09	3,7	
2005M08	3,3	3,4
2005M07	3,3	
2005M06	3,1	
2005M05	3,1	
2005M04	3,5	
2005M03	3,4	
2005M02	3,3	
2005M01	3,1	
2004M12	3,2	3,3
2004M11	3,5	
2004M10	3,6	
2004M09	3,2	

	Annual variation	Annual average
2004M08	3,3	
2004M07	3,4	
2004M06	3,5	
2004M05	3,4	
2004M04	2,7	
2004M03	2,1	
2004M02	2,1	2,7
2004M01	2,3	
2003M12	2,6	
2003M11	2,8	
2003M10	2,6	
2003M09	2,9	
2003M08	3,0	
2003M07	2,8	
2003M06	2,7	
2003M05	2,7	3,2
2003M04	3,1	
2003M03	3,7	
2003M02	3,8	
2003M01	3,7	
2002M12	4,0	
2002M11	3,9	
2002M10	4,0	
2002M09	3,5	
2002M08	3,6	3,7
2002M07	3,4	
2002M06	3,4	
2002M05	3,6	
2002M04	3,6	
2002M03	3,1	
2002M02	3,1	
2002M01	3,1	
2001M12	2,7	
2001M11	2,7	3,2
2001M10	3,0	
2001M09	3,4	
2001M08	3,7	
2001M07	3,9	

	Annual variation	Annual average
2001M06	4,2	
2001M05	4,2	
2001M04	4,0	4,0
2001M03	3,9	
2001M02	3,8	
2001M01	3,7	

	Annual variation	Annual average
2000M12	4,0	
2000M11	4,1	
2000M10	4,0	
2000M09	3,7	
2000M08	3,6	3,4
2000M07	3,6	

	Annual variation	Annual average
2000M06	3,4	
2000M05	3,1	
2000M04	3,0	

From the previous table, the inter annual result turns out to be a 2,4% of average increase, which will be maintained throughout all the viability studies of the present report.

2.4.4. CALCULATION OF THE CASH FLOWS

The wireless tunnel only gives an economic benefit in the initial investment, generating negative cash flows throughout the rest of its lifetime.

It could be considered an additional little benefit due to the fact that the maintenance is simpler and reduces the use of elevation vehicles during the maintenance; however, this little saving is counterbalanced by the higher cost of material acquisition related to the replacement pieces, since the equipment to maintain are more expensive.

The following table shows the cash flows referred to the year of the cash flow and to the year of the initial investment (a 2,4% of inflation has been considered).

CASH FLOWS					
Year	€/KWh	Consumption [kWh]	Cash flow	Cash flow in year 0	Accumulated
0	0,1217583	0	10.635,81 €	10.635,81 €	10.635,81 €
1	0,12516513	31.540,38	-3.947,76 €	-3.855,23 €	6.780,58 €
2	0,12866728	31.540,38	-4.058,21 €	-3.870,22 €	2.910,36 €
3	0,13226743	31.540,38	-4.171,77 €	-3.885,26 €	-974,89 €
4	0,13596831	31.540,38	-4.288,49 €	-3.900,36 €	-4.875,26 €

Table 2.4.4.I. Cash flows for the Wireless tunnel.

The cash flows shows that at the third year after the investment, the accumulated costs are higher than the initial saving; thus, the implementation of a wireless tunnel is clearly not viable.

3. LIGHTING PERMANENT CONTROL

Within the task T4.2 in the WP4 it is analysed the economic viability for the implantation of a system that adapts permanently the tunnel's lighting to the traffic conditions.

The proposed system achieves a higher energy efficiency through the adjustment, in each instant and continuously, of the lighting intensity depending on the traffic conditions.

3.1. INITIAL INVESTMENT

After revising the criteria established in the standard CIE-88 for the designing of the lighting system, it can be pointed out that:

- The traffic density affects the luminance to attain in the inside of the tunnel only in the case of unidirectional tunnels with a traffic rate above 500 vehicles and below 1500 vehicles per hour and lane. In the case of bidirectional tunnels, the limits are between 400 and 1000 vehicles per hour and lane.

- The designing of the daytime lighting is affected by the traffic speed but not by the traffic density.

As the velocity in the inside of the tunnels can be rather constant, there is no interest in making investments in systems that adapt the daytime lighting to the tunnel’s authorised velocity.

It is only interesting to assess an adaptation system for the internal luminance of the tunnel to the traffic density and it is only interesting to study it when the traffic density is variable.

In order to place in operation a system with these characteristics, the first need is to have an internal lighting system able to vary its intensity gradually or continuously and with a rapid response time.

There are electronic ballasts for HSP (High Sodium Pressure) and metal halide lamps that allow the regulation of the luminous intensity but with certain margins and temporary alterations of the light, which is not advisable for this kind of applications.

Currently, both the fluorescent and the LED technology verify the desired requirements for a variable adjustment and the rapid response.

For the study of the economic viability of the regulation of the internal lighting with the traffic density, it is worthless to analyse the kind of technology installed, since the increase in the cost related to the installation of the electronic control ballasts is similar for both technologies.

The chosen tunnel is the Nievares tunnel, which is composed of two unidirectional tubes with two lanes per road. The total traffic rate for this tunnel is 44.000 vehicles per day and it is within the range where the best result is expected.

Additionally, the Nievares tunnel has a considerable length (2.300 m); thus,the permanent lighting has an important relevance within the total consumption of the tunnel.

The initial investment for the update of the internal lighting of the Nievares tunnel with a system able to make a continuous regulation would be:

INVESTMENT COST				
Concept	**Unit**	**Measure**	**Unitary Price (€/ud)**	**Total price (€)**
Electronic ballast	unit	528	116,91	61.728,48
Permanent management system	unit	1	8.595,00	8.595,00
Algorithm	unit	1	2.469,00	2.469,00
Traffic control	unit	2	3.456,60	6.913,20
			TOTAL	79.705,68

Table 3.1.I. Initial investment for the continuous control of the lighting system.

Within the investment, it is included the corresponding part of the installation of two stations for the data acquisition at the entrances of the tunnel, in order to get the information of the traffic density and the cost of the implementation of the control algorithm.

It is important to highlight that currently, this tunnel has internal HSP luminaries that don't allow the desired regulation. However, including in the budget the replacement of these luminaries by others with LED technology would affect the viability study; thus, the LED technology is a measure of global efficiency that is not desired to be assessed.

3.2. CASH FLOWS

Through simulations it is calculated the energetic consumption that the tunnel would have with continuous regulation and then, the results are compared with the consumption that the tunnel would have with a conventional regulatory system.

For this purpose, the mathematical model developed in the WP2 must be modified to include an algorithm of regulation that follows the criteria established in the CIE-88 dynamically with the variation of the traffic rate.

The results are shown in the Graphics of the **Figure 3.2.I:**

Conventional regulation	Continuous regulation

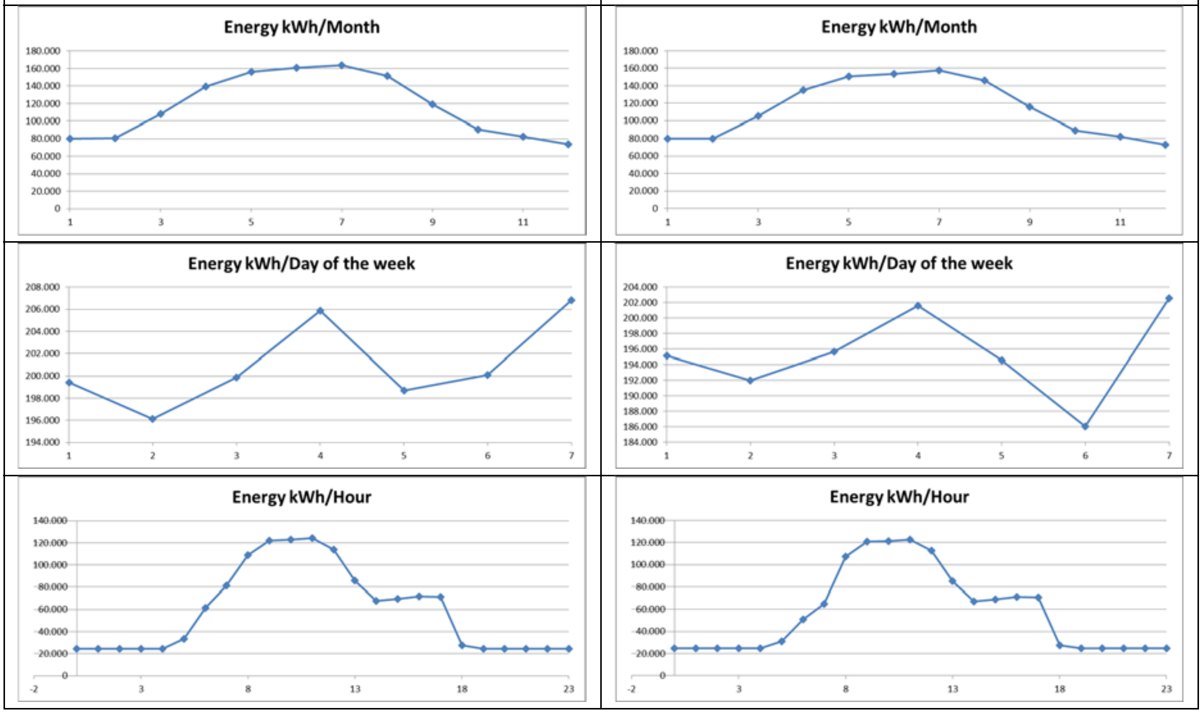

Figure 3.2.I. Consumption curves before and after the continuous regulation.

The results indicate that the annual electric consumption would vary from 1.406.862 kWh to 1.367.466 kWh, being reduced in 39.396 kWh.

The consumption is reduced less than expected due to the fact that usually in tunnels with high traffic rate, this parameter doesn't vary significantly except during night time, during which the lighting level is reduced both with the continuous regulation and with the conventional regulation.

In the consumption graphics throughout the days of the week of the **Figure 3.2.I**, it is appreciated clearly that the consumption reduction takes place mainly on Saturday; thus, is can be applied a reduction of the lighting level and the consumption diminishes.

This consumption reduction would give the following cash flows:

CASH FLOWS					
Year	€/KWh	Consumption [kWh]	Cash flow	Cash flow in year 0	Accumulated
0	0,1217583	0	-79.705,68 €	-79.705,68 €	-79.705,68 €
1	0,12516513	39.396	4.931,01 €	4.815,44 €	-74.890,24 €
2	0,12866728	39.396	5.068,98 €	4.834,15 €	-70.056,09 €
3	0,13226743	39.396	5.210,81 €	4.852,94 €	-65.203,15 €
4	0,13596831	39.396	5.356,61 €	4.871,81 €	-60.331,34 €
5	0,13977274	39.396	5.506,49 €	4.890,74 €	-55.440,60 €
6	0,14368362	39.396	5.660,56 €	4.909,75 €	-50.530,85 €
7	0,14770392	39.396	5.818,94 €	4.928,84 €	-45.602,01 €
8	0,15183672	39.396	5.981,76 €	4.948,00 €	-40.654,02 €
9	0,15608515	39.396	6.149,13 €	4.967,23 €	-35.686,79 €
10	0,16045245	39.396	6.321,18 €	4.986,54 €	-30.700,25 €
11	0,16494196	39.396	6.498,05 €	5.005,92 €	-25.694,33 €
12	0,16955708	39.396	6.679,87 €	5.025,38 €	-20.668,96 €
13	0,17430133	39.396	6.866,78 €	5.044,91 €	-15.624,05 €
14	0,17917833	39.396	7.058,91 €	5.064,52 €	-10.559,53 €
15	0,18419178	39.396	7.256,42 €	5.084,20 €	-5.475,32 €
16	0,18934552	39.396	7.459,46 €	5.103,97 €	-371,36 €
17	0,19464346	39.396	7.668,17 €	5.123,81 €	4.752,45 €
18	0,20008963	39.396	7.882,73 €	5.143,72 €	9.896,17 €
19	0,2056882	39.396	8.103,29 €	5.163,72 €	15.059,89 €
20	0,21144341	39.396	8.330,02 €	5.183,79 €	20.243,67 €

Table 3.2.I. Cash flows for the continuous control lighting system.

The cash flows indicate that the investment doesn't return till a bit longer than 16 years and this, without taking into account that the ballasts' lifetime is 10 years, period from which it is needed to proceed to replace part of the installation.

The economic viability of the continuous control measure of the lighting system is not satisfactory in tunnels unless they have high traffic densities and at the same time they vary strongly during the day, where this measure may be positive.

4. LIGHTING ON-OFF CONTROL

Within the task T4.3 of the WP4 it is analysed the economic viability of the implantation of an On-Off adaptation system of the tunnel's lighting depending on the traffic conditions.

The proposed system achieves a higher energy efficiency through the switching off of the lighting system when there is no traffic inside the tunnel.

4.1. INITIAL INVESTMENT

In order to put in practice a system with those characteristics, the first need is to have an internal lighting system with a rapid response time and without consumption peaks during the switching on of the luminaries. It is also desirable that the lifetime of the devices is not affected by the switching on cycles done.

Currently, both the fluorescent technology and the LED technology verify the desirable requirements of the rapid response time, although the fluorescent technology can present a light reduction in the average lifetime of the luminaries because of the switching on.

For the economic viability study, the used technology is worthless because the increment in the cost for installing devices with on-off control is similar for both technologies.

The tunnels with low density traffic rates and low length are the ones with an expected best response of this measure.

The chosen tunnel for this study is the Caldas tunnel, which is composed of a bidirectional tube with two lanes (one per sense). The total traffic rate of this tunnel is 1.300 vehicles per day.

The necessary investment for the updates of the electric switchboards and the management system to implement the on-off regulation system in the Caldas tunnel would be:

INVESTMENT COST				
Concept	**Unit**	**Measure**	**Unitary Price (€/ud)**	**Total price**
Management system	unit	1	3.438,00	3.438,00
Electric modifications	unit	1	1.561,70	1.561,70
Algorithm	unit	1	1.061,70	1.061,70
Traffic control (1 lane)	unit	2	2.304,40	4.608,80
			TOTAL	10.670,20

Table 4.1.I. Initial investment for the on-off lighting control.

Within the investment, it is included the corresponding part of the installation of two station for the data acquisition at the entrances of the tunnel, in order to get the information of the traffic density and the cost of the implementation of the control algorithm.

It is important to highlight that the tunnel currently has internal HSP luminaries with a reaction time that is too slow for the on-off control. However, including in the budget the replacement of these luminaries by others with LED technology would affect the viability study; thus, the LED technology is a measure of global efficiency that is not desired to be assessed.

4.2. CASH FLOWS FOR THE TOTAL ON-OFF CONTROL

Through simulations it is calculated the energetic consumption that the tunnel would have with the on-off regulation and then, the results are compared with the consumption that the tunnel would have with a conventional regulatory system.

For this purpose, the mathematical model developed in the WP2 must be modified in order to include the switching off of the lighting when there is no vehicle inside.

The results are shown in the graphics of the **Figure 4.2.I:**

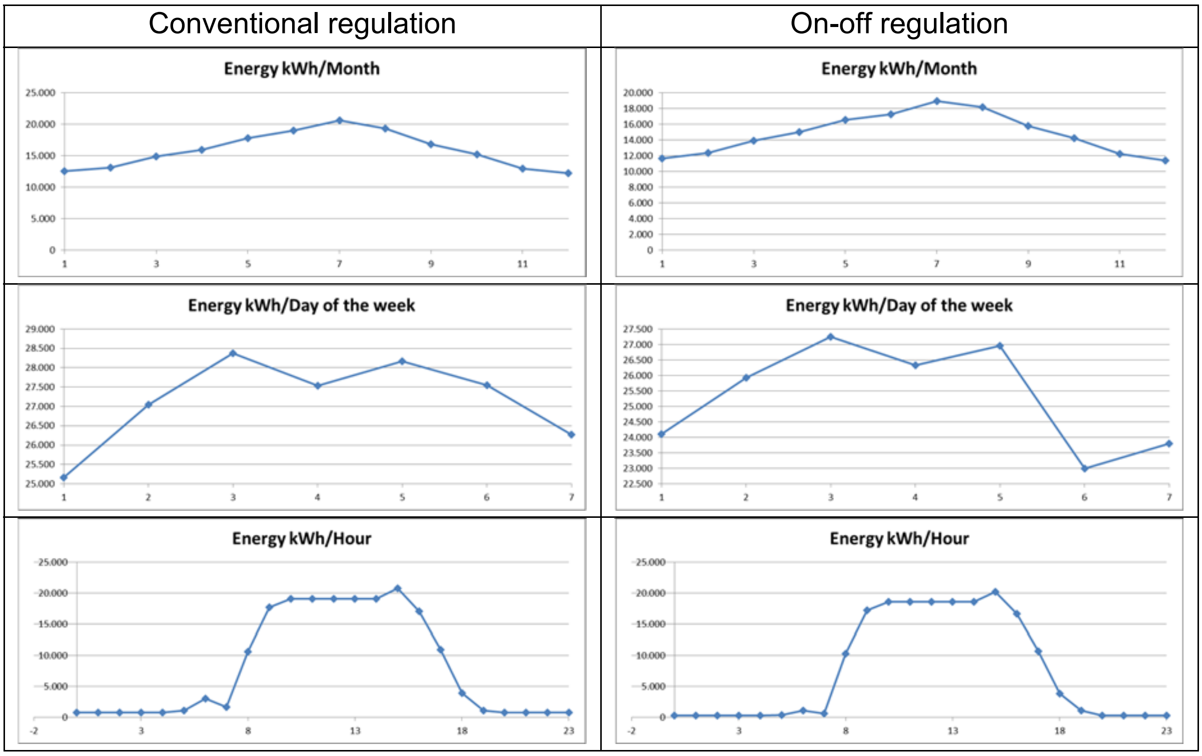

Figure 4.2.I. Consumption curves before and after the on-off regulation.

The results indicate that the electric consumption would vary from 190.109 kWh to 177.371 kWh, with a reduction of 12.738 kWh, which means a 6,7%.

In the consumption graphic throughout the days of the week of the **Figure 4.2.I** it can be appreciated that the consumption reduction is produced throughput all the days of the year but with more intensity on Saturdays.

This reduction would lead to the following cash flows:

CASH FLOWS					
Year	€/KWh	Consumption [kWh]	Cash flow	Cash flow at year 0	Accumulated
0	0,1217583	0	-10.670,20 €	-10.670,20 €	-10.670,20 €
1	0,12516513	12.738	1.594,35 €	1.556,99 €	-9.113,21 €
2	0,12866728	12.738	1.638,96 €	1.563,04 €	-7.550,18 €
3	0,13226743	12.738	1.684,82 €	1.569,11 €	-5.981,06 €
4	0,13596831	12.738	1.731,96 €	1.575,21 €	-4.405,85 €
5	0,13977274	12.738	1.780,43 €	1.581,34 €	-2.824,52 €
6	0,14368362	12.738	1.830,24 €	1.587,48 €	-1.237,03 €
7	0,14770392	12.738	1.881,45 €	1.593,65 €	356,62 €
8	0,15183672	12.738	1.934,10 €	1.599,85 €	1.956,47 €
9	0,15608515	12.738	1.988,21 €	1.606,07 €	3.562,53 €
10	0,16045245	12.738	2.043,84 €	1.612,31 €	5.174,84 €

Table 4.2.I.- Cash flows of the on-off lighting control.

The cash flows reveal that the investment returns in less than 7 years, being an investment that doesn't need to be renewed after these 7 years and whose maintenance doesn't require any additional cost apart from the usual in a conventional installation.

The main disadvantage of this method is the lack of standardised regulation that permits the complete switch off of the lighting system.

As an alternative, it is also studied the cash flows in case of switching off only the daytime lighting if no vehicles approaches the tunnel, in such a way that it would remain just the permanent lighting luminaries.

4.3. CASH FLOWS FOR THE PARTIAL ON - OFF CONTROL

Through simulations it is calculated the energetic consumption that the tunnel would have with the partial on-off regulation and then, the results are compared with the consumption that the tunnel would have with a conventional regulatory system.

For this purpose, the mathematical model developed in the WP2 must be modified in order to include the switching off of the lighting when there is no vehicle inside.

The results are shown in the graphics of the **Figure 4.3.I:**

Conventional regulation	Partial on – off regulation

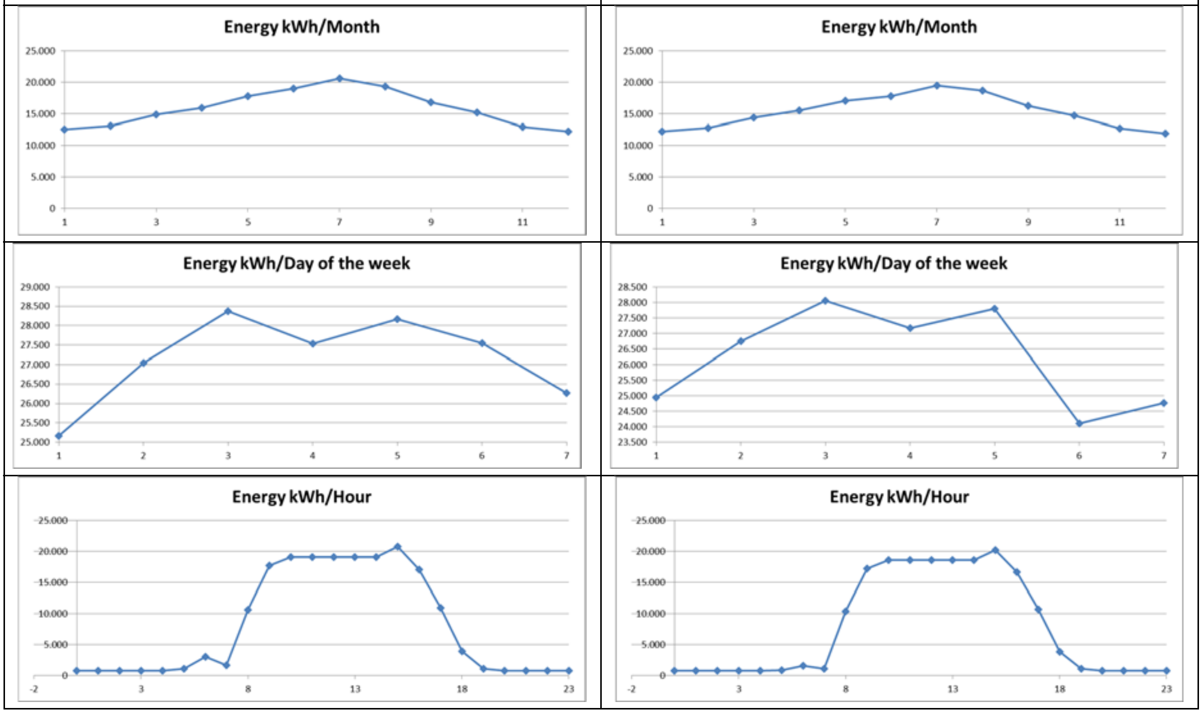

Figure 4.3.I. Consumption curves before and after the partial on-off regulation.

The results indicate that the electric consumption would pass from 190.109 kWh to 183.574 kWh, with a reduction of 6.535 kWh, which means a 3,4%.

The consumption reduction is practically a half of the one obtained with the complete on-off regulation, although this ratio is quite depending on the tunnel's length.

This consumption reduction would lead to the following cash flows:

CASH FLOWS					
Year	€/KWh	Consumption [kWh]	Cash flow	Cash flow at year 0	Accumulated
0	0,1217583	0	-8.791,29 €	-8.791,29 €	-8.791,29 €
1	0,12516513	6.535	817,95 €	798,78 €	-7.992,51 €
2	0,12866728	6.535	840,84 €	801,89 €	-7.190,62 €
3	0,13226743	6.535	864,37 €	805,01 €	-6.385,61 €
4	0,13596831	6.535	888,55 €	808,13 €	-5.577,48 €
5	0,13977274	6.535	913,41 €	811,28 €	-4.766,20 €
6	0,14368362	6.535	938,97 €	814,43 €	-3.951,78 €
7	0,14770392	6.535	965,25 €	817,59 €	-3.134,18 €
8	0,15183672	6.535	992,25 €	820,77 €	-2.313,41 €
9	0,15608515	6.535	1.020,02 €	823,96 €	-1.489,45 €
10	0,16045245	6.535	1.048,56 €	827,17 €	-662,28 €
11	0,16494196	6.535	1.077,90 €	830,38 €	168,10 €
12	0,16955708	6.535	1.108,06 €	833,61 €	1.001,71 €
13	0,17430133	6.535	1.139,06 €	836,85 €	1.838,56 €
14	0,17917833	6.535	1.170,93 €	840,10 €	2.678,66 €

Table 4.3.I Cash flows with the partial on – off regulation.

The cash flows indicate that the investment returns in less than 11 years.

4.4. INVESTMENT ECONOMIC PARAMETERS

For both alternatives, total and partial on – off control, the most used economic parameters for an investment are calculated, that is, the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Payback Period of Investment (PPI).

Lifetime [years]	NPV [€]	IRR [%]	PPI [años]
20	21.646,66 €	16,5%	6,8

Table 4.4.I. Investment economic parameters for a total on – off control.

Lifetime [years]	NPV [€]	IRR [%]	PPI [años]
20	7.788,29 €	9,4%	10,8

Table 4.4.II. Investment economic parameters for a partial on – off control.

In both cases a 20 year – lifetime has been considered, although actually most of the elements would be able to remain operating for longer periods of time.

5. SYSTEM TO USE THE EXTERNAL LUMINOSITY

The daytime lighting consumes electric energy to convert it into luminous energy when more solar energy is available outside of the tunnel; thus it is evident that if it was possible to redirect the external light towards the inside of the tunnel it could be possible to eliminate the consumption of this installation.

Within the task T4.4 of the WP4, it is analysed the economic viability of the implantation of a system that uses the external lighting to replace the daytime lighting.

5.1. INITIAL INVESTMENT

Since it is an innovative system with no precedents, an estimation for the system's dimensions must be done for a specific tunnel, in this case, the Folgoso tunnel.

For an authorised speed of 80 km/h, according to the L20 method described in the CIE-88 Annex 1, the illuminance in the tunnel's entrance is calculated by multiplying L20 by 0,06; that is Lth=0,06*L20.

The tunnel's lighting decreases its intensity as the entrance gets further, following the adaptation curve shown in **Figure 5.1.I.**

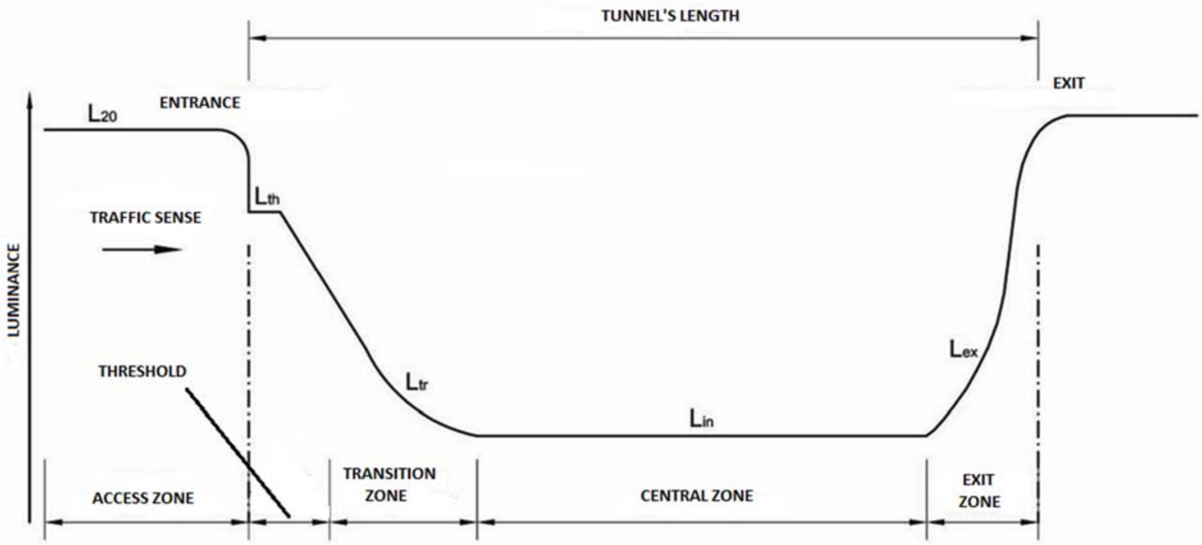

Figure 5.1.I. Adaptation curve for a unidirectional tunnel.

In a long tunnel with a L20 equal to 5.000 Cd/m^2, the integration of the luminance provided by the daytime lighting throughout the tunnel's length gives a value of 19800 Cd/m. If it is considered a 10m width of the road, it is obtained 198000 Cd of luminous intensity.

In order to obtain that luminous intensity with the aid of the external conditions, it would be necessary to have a surface of 198000/5000=39,6 m^2.

The system must be composed of diverse elements in charge of:

- Capture the external luminous intensity in a 40m2 surface.
- Concentrate the captured light to facilitate the transportation.
- Transport the concentrated light in a way above the internal signalisation metallic supports.
- Spread and blur the transported light over the tunnel's length according to the adaptation's curve.

First, it is supposed that the 40m^2 of capture surface are divided into 6 different equipment with similar characteristics, being the associated cost the one shown in **Table 5.1.I.**

INVESTMENT COST				
Concept	**Unit**	**Measure**	**Unitary Price (€/ud)**	**Total price (€)**
Metallic support	unit	6	4.600,00	27.600,00
Capturing solar dish	unit	6	42.000,00	252.000,00
Serve engine	unit	12	1.200,00	14.400,00
Control system	unit	1	5.300,00	5.300,00
Transport pipe	unit	697	132,00	92.004,00
Diffusion system	unit	6	35.000,00	210.000,00
Adjustment and tests	unit	1	3.975,00	3.975,00
			TOTAL	605.279,00

Table 5.1.I. Budget for the investment of the system for the use of the external light.

The most important costs are due to the complexity in the manufacturing of the mirrors that will concentrate the light and will subsequently spread and blur it over the road.

5.2. CASH FLOWS

Through simulations it is calculated the energetic consumption that the tunnel would have with the system for the use of the external luminosity and then, the results are compared with the consumption that the tunnel would have with a conventional regulatory system.

In this case it is not necessary to modify the mathematical model that was developed in the WP2, since it allows to force the access luminance to 0 cd/m^2.

The results that have been obtained are shown in the graphics of the **Figure 5.2.I.**

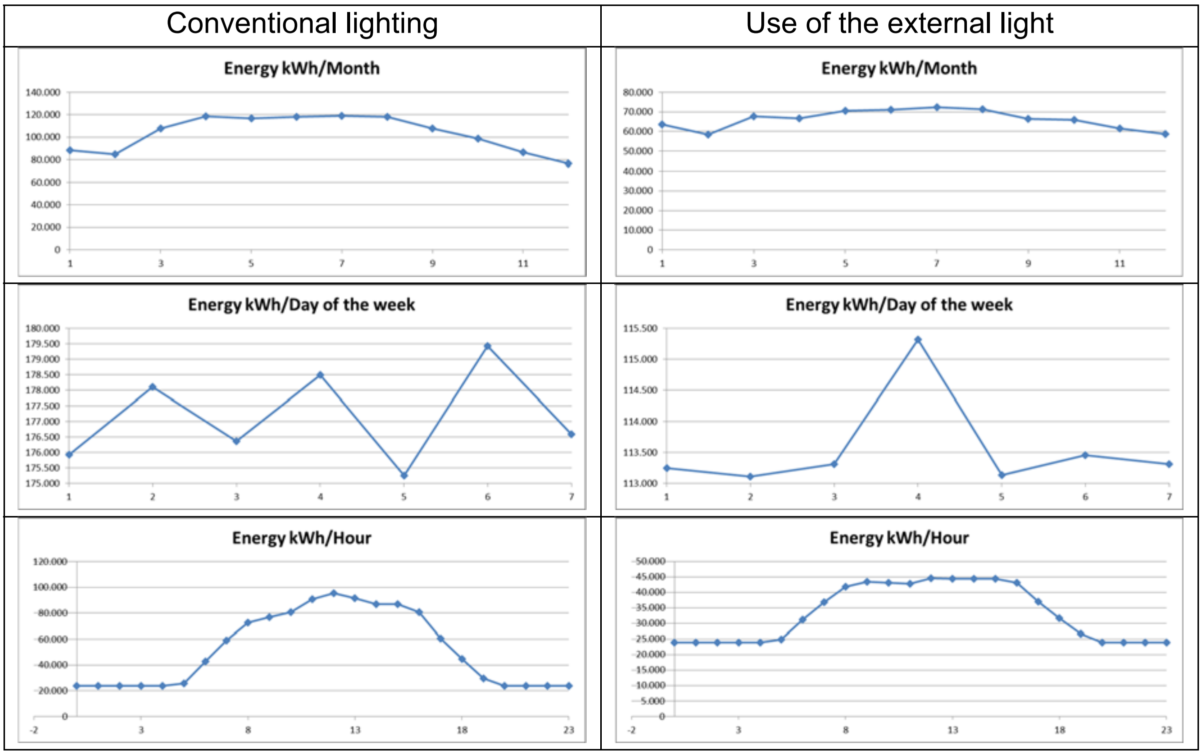

Figure 5.2.I. Curvas de consumo antes y después del aprovechamiento de la luz exterior.

The results indicate that the annual electric consumption would pass from 1.240.153 kWh to 794.887 kWh, with a reduction of 445.266 kWh, which represents a 35,9%.

There are always some costs related to the installation of a new system, especially when the dimensions are the ones of the system being studied, which in this case are due to:

- Need of cleaning of the reflecting surfaces and the protection glass. This is a critic operation for the system's efficiency and that must be done, at least, with a monthly frequency.

- Need of lubrication of the moving parts. This operation must be done at least with an annual frequency, with the revision of the mechanical elements supervision.

Both maintenance operation would be quantified in a unique annual unit of 12.500€, which will be incremented only because of the inflation.

The cash flows associated to the initial investment would be the ones shown in **Table 5.2.I**.

CASH FLOWS						
Year	€/KWh	Consumption [kWh]	Maintenance [€]	Cash flow	Cash flow at year 0	Accumulated
0	0,1217583	0	0	-605.279,00 €	-605.279,00 €	-605.279,00 €
1	0,12516513	445.266	12.500	43.231,78 €	42.218,53 €	-563.060,47 €
2	0,12866728	445.266	12.800	57.291,17 €	54.637,11 €	-508.423,36 €
3	0,13226743	445.266	13.107	58.894,19 €	54.849,49 €	-453.573,87 €
4	0,13596831	445.266	13.422	60.542,07 €	55.062,69 €	-398.511,18 €
5	0,13977274	445.266	13.744	62.236,05 €	55.276,72 €	-343.234,46 €
6	0,14368362	445.266	14.074	63.977,43 €	55.491,58 €	-287.742,89 €
7	0,14770392	445.266	14.412	65.767,53 €	55.707,27 €	-232.035,62 €
8	0,15183672	445.266	14.757	67.607,73 €	55.923,80 €	-176.111,82 €
9	0,15608515	445.266	15.112	69.499,41 €	56.141,18 €	-119.970,64 €
10	0,16045245	445.266	15.474	71.444,02 €	56.359,39 €	-63.611,25 €
11	0,16494196	445.266	15.846	73.443,05 €	56.578,47 €	-7.032,78 €
12	0,16955708	445.266	16.226	75.498,00 €	56.798,38 €	49.765,60 €
13	0,17430133	445.266	16.615	77.610,46 €	57.019,16 €	106.784,76 €
14	0,17917833	445.266	17.014	79.782,02 €	57.240,79 €	164.025,55 €
15	0,18419178	445.266	17.422	82.014,34 €	57.463,28 €	221.488,83 €

Table 5.2.I.- Cash flows for the investment in a system that uses the external light.

The cash flows indicate that the investment returns in little more than 11 years.

5.3. INVESTMENT ECONOMIC PARAMETERS

The most used economic parameters are calculated:

Lifetime [years]	NPV [€]	IRR [%]	PPI [años]
25	808.574,70 €	10,3%	11,1

Table 5.3.I.- Economic parameters for the investment in a system that uses the external light.

A 25 year – lifetime has been considered, from which the reflective surfaces may have some problems, such as the corrosion or deterioration, needing a replacement.

6. DATABASE OF REAL TIME CONSUMPTION

Within the task T4.5 of the WP4, it is studied the cost for the implementation of a registration system of the consumption, which is similar to the one used in the WP2, but with a maintenance software. This sort of system can give an advice of malfunctioning that leads to big changes in consumption and foresee the fatigue of the equipment due to changes in the consumption patterns.

6.1. INITIAL INVESTMENT

Thanks to the experience obtained from the development of the consumption registration system, it can be rapidly estimated a budget for the implantation of a similar system, but fixed:

INVESTMENT COST				
Concept	**Unit**	**Measure**	**Unitary price**	**Total price**
Network analyser	unit/CT	1	527,08	527,08
16 circuits detector	unit/CT	1	603,76	603,76
8 analogic inputs module	unit/CT	1	153,35	153,35
Installation	unit/CT	1	1.698,40	1.698,40
Data logger	unit/CT	1	484,58	484,58
Modem	unit/CTS	1	77,83	77,83
Box	unit/CT	1	175,56	175,56
Extension of the software	unit/CT	1	1.646,00	1.646,00
Basic software	unit	1	5.617,00	5.617,00
			TOTAL	10.983,56

Table 6.1.I.- Initial investment for the consumption database in TR.

The investment of the **Table 6.1.I** is referred to the needed equipment for a tunnel having a unique transformation Centre with no communication network. In each case, depending on the installations of the chosen tunnel, it may be necessary to increase the investment according to:

- The units of the type unit/CT must be multiplied by the number of Transformation Centres.
- The units of the type unit/CTS must be multiplied by the number of transformation centres not having an Ethernet communication.

6.2. CASH FLOWS

In order to assess the economic viability of the proposal, the initial investment must be compared with the benefits obtained in the corrective and preventive maintenance framework.

The economic benefits obtained by the system are:

- Reduction of the installations surveillance cost, as a part of the defects will be detected by the proposed system, generating an alarm in the control centre.
- Reduction of the energetic cost associated to malfunctioning of the system. The automatic detection of defects in the installations increase the response time and, therefore, the additional costs that may arise.

- Reduction of the energetic costs of the equipment, that deteriorate their efficiency as time goes by. A system like the proposed one allows to calculate the optimal moment for the replacement of this sort of equipment.

An average tunnel needs surveillance of its installations of 30 minutes per day, each day of the year. If the surveillance hour is quantified as 56,7 €/h, the annual cost of the surveillance is 365/2*56,7 = 10.347,75€.

The implementation of this system would allow to reduce the intensity of the surveillance a 15%, which means an annual saving of 1.552,16 €.

There are always associated to a system like the one proposed some maintenance costs, which are quantified as a 10% of the initial investment value (1.098,36€).

The savings in surveillance minimised after the additional maintenance costs are considered, lead to savings in maintenance of 453,80 € per year.

A common fail in a tunnel's installations is the blockage of the daytime lighting in the ON position because of malfunction of the luminancimeter or the control system. These fails can arise once per year and are traduced in the unnecessary switch on of the daytime lighting during the night before the fail's detection by the surveillance operator.

The immediate detection in a tunnel like Folgoso, which has 350 kW in daytime lighting power, would be traduced in average savings of 12h of operation per year (350*12=4.200 kWh).

Another fail likely to appear is the blockage of one of the jets in the ON position because of a failure of the environment detectors or the control system. Giving this fail the same frequency as for the previous fail and taking into account that a jet fan power is around 45 kW, a saving of 45*12=540 kWh is calculated.

The combined detection of both lighting switching on and ventilation allow annual savings of 4.740 kWh.

The main installation that gets deteriorated its efficiency with the time is the lighting and, more specifically, in the case of discharge lamps (like HSP lamps, for example), it could be interesting to know the optimal instant for its replacement.

However, the benefit currently obtained by the replacement of this installation in their optimal moment gets lower and so on, since it has become more common to replace it by LED luminaries, with a longer lifetime. For this reason, the economic benefit that turns out is neglected.

This measure would mean the cash flows shown in the **Table 6.2.I**.

CASH FLOWS						
Year	€/KWh	Consumption [kWh]	Maintenance[€]	Cash flow	Cash flow at year 0	Accumulated
0	0,1217583	0	0,00 €	-10.983,56 €	-10.983,56 €	-10.983,56 €
1	0,12516513	4.740	453,80 €	1.047,08 €	1.022,54 €	-9.961,02 €
2	0,12866728	4.740	464,69 €	1.074,57 €	1.024,79 €	-8.936,22 €
3	0,13226743	4.740	475,84 €	1.102,79 €	1.027,05 €	-7.909,17 €
4	0,13596831	4.740	487,26 €	1.131,75 €	1.029,32 €	-6.879,85 €
5	0,13977274	4.740	498,96 €	1.161,48 €	1.031,60 €	-5.848,24 €
6	0,14368362	4.740	510,93 €	1.191,99 €	1.033,89 €	-4.814,35 €
7	0,14770392	4.740	523,20 €	1.223,31 €	1.036,19 €	-3.778,17 €
8	0,15183672	4.740	535,75 €	1.255,46 €	1.038,49 €	-2.739,68 €
9	0,15608515	4.740	548,61 €	1.288,45 €	1.040,80 €	-1.698,87 €
10	0,16045245	4.740	561,78 €	1.322,32 €	1.043,13 €	-655,74 €
11	0,16494196	4.740	575,26 €	1.357,08 €	1.045,46 €	389,72 €
12	0,16955708	4.740	589,07 €	1.392,77 €	1.047,80 €	1.437,52 €
13	0,17430133	4.740	603,20 €	1.429,39 €	1.050,15 €	2.487,67 €
14	0,17917833	4.740	617,68 €	1.466,99 €	1.052,51 €	3.540,18 €
15	0,18419178	4.740	632,50 €	1.505,57 €	1.054,88 €	4.595,06 €
16	0,18934552	4.740	647,69 €	1.545,18 €	1.057,26 €	5.652,32 €
17	0,19464346	4.740	663,23 €	1.585,84 €	1.059,64 €	6.711,96 €
18	0,20008963	4.740	679,15 €	1.627,57 €	1.062,04 €	7.774,00 €
19	0,2056882	4.740	695,45 €	1.670,41 €	1.064,45 €	8.838,45 €
20	0,21144341	4.740	712,14 €	1.714,38 €	1.066,86 €	9.905,31 €

Table 6.2.I.- Cash flows from the consumption database in TR.

The cash flows indicate that the investment returns in less than 11 years.

6.3. INVESTMENT ECONOMIC PARAMETERS

The main investment economic parameters are calculated:

Lifetime [years]	NPV [€]	IRR [%]	PPI [años]
15	4.595,06 €	7,2%	10,6

Table 6.3.I.- Economic parameters from the consumption database in TR.

As it can be appreciated in the initial budget, a great part of the system is composed by a management software, which has a marked tendency to the obsolescence; thus, it is considered a lifetime of only 15 years.

7. COMPUTATIONAL CONSUMPTION MODELIZATION

The mathematical model for a tunnel's consumption that was done in the WP2 is implemented through worksheets and excel macros with a little or no possibility for the distribution and sale.

In this task it is studied the possibility and the cost of the implementation of the mathematical model for the consumption in a software with easy distribution and equipped with means for the licences management and updates.

7.1. INITIAL INVESTMENT

Taking into account the time required to elaborate the mathematical model in a worksheet, it is considered as necessary the development of a software during a 1 month – time, with the participation of a developer, an analyst and the expert in the tunnels' domain who created the original model. The cost is shown in the **Table 7.1**.

In order to guarantee the intellectual protection of the model, the model must be provided with a commercial software for the licences management.

INVESTMENT COST				
Concept	**Unit**	**Measure**	**Unitary Price**	**Total price**
Programmer analyst	h	40	65,78	2.631,20
Programmer	h	160	42,02	6.723,20
Tunnels engineer	h	30	68,35	2.050,50
Licences management software	h	1	1.121,00	1.121,00
			TOTAL	12.525,90

Table 7.1.I.- Initial investment for the computational consumption modelling.

7.2. CASH FLOWS

The cash flows relative to the measure would be:

- Income due to the sales of the software.
- Income due to assistance and training.
- Costs relative to assistance and training.
- Costs due to promoting the product.
- Costs due to updates.

The potential market for the software is composed of tunnel managers and specialised engineering companies in the elaboration of projects in the tunnels domain. The laws and standards that have been used for the elaboration of the model restrict its use to the EU.

Tunnels are usually managed mostly by public entities and specialised engineering companies are usually reduced; thus, the number of clients are rather small, about 10 per country. Since currently the EU is composed of 28 countries, it can be estimated the existence of 180 potential clients.

A marketing campaign is not effective for such reduced number of clients; thus, it is considered that it will only reach to contact a 10th part of the potential clients per year. It can be foreseen as well that only 1 in every 5 contacts will close a sale. With every sale closed it can be foreseen as well that a technical support staff will be hired for a 2 years – time, with a cost estimated equal to a 30% of the licence.

After 10 years of sales of the product, all the potential customers will have been contacted and sales will end. Two years later, the requests for a technical assistance will finish and the lifetime of the product will be over.

The technical support and the updates of the software are done by the programmer, who will be hired 2 h per week the first 11 years. The last year the need of the programmer will be reduced to a half.

Under these assumptions, it is sought a sale price that allows an minimum of 5% IRR, reaching 724,65€ per licence and the cash flows shown in the **Table 7.2.I**.

CASH FLOWS								
Year	Licence [unit]	Price [€/lic]	Support [unit]	Price [€/sop]	Programmer	Cash flow	Cash flow at year 0	Accumulated
0	0	0,00 €	0			-12.525,90 €	-12.525,90 €	-12.525,90 €
1	5,6	724,65 €	0	217,40 €	-4.370,08 €	-312,04 €	-304,73 €	-12.830,63 €
2	5,6	742,04 €	5,6	222,61 €	-4.474,96 €	927,10 €	884,15 €	-11.946,47 €
3	5,6	759,85 €	11,2	227,96 €	-4.582,36 €	2.225,90 €	2.073,03 €	-9.873,44 €
4	5,6	778,09 €	11,2	233,43 €	-4.692,34 €	2.279,32 €	2.073,03 €	-7.800,41 €
5	5,6	796,76 €	11,2	239,03 €	-4.804,95 €	2.334,03 €	2.073,03 €	-5.727,38 €
6	5,6	815,88 €	11,2	244,77 €	-4.920,27 €	2.390,04 €	2.073,03 €	-3.654,35 €
7	5,6	835,46 €	11,2	250,64 €	-5.038,36 €	2.447,40 €	2.073,03 €	-1.581,32 €
8	5,6	855,52 €	11,2	256,65 €	-5.159,28 €	2.506,14 €	2.073,03 €	491,71 €
9	5,6	876,05 €	11,2	262,81 €	-5.283,10 €	2.566,29 €	2.073,03 €	2.564,74 €
10	5,6	897,07 €	11,2	269,12 €	-5.409,90 €	2.627,88 €	2.073,03 €	4.637,78 €
11	0	918,60 €	11,2	275,58 €	-5.539,73 €	-2.453,23 €	-1.889,90 €	2.747,88 €
12	0	940,65 €	5,6	282,19 €	-2.836,34 €	-1.256,05 €	-944,95 €	1.802,93 €

Table 7.2.I.- Cash flows for 5,6 annual licences sales.

The indicated sale price is competitive but it could only be maintained with a sales rate of at least 5,6 licences per year.

If it is sought a sale price that assures a minimum 5% IRR for sales reduced to the half, the sale price is 1.449,37 € per licence and the annual cash flows are shown in the **Table 7.2.II.**

CASH FLOWS								
Year	Licences [unit]	Price [€/lic]	Supports [unit]	Price [€/sop]	Programmer	Cash flow	Cash flow at year 0	Accumulated
0	0	0,00 €	0			-12.525,90 €	-12.525,90 €	-12.525,90 €
1	2,8	1.449,37 €	0	434,81 €	-4.370,08 €	-311,85 €	-304,54 €	-12.830,44 €
2	2,8	1.484,15 €	2,8	445,25 €	-4.474,96 €	927,36 €	884,40 €	-11.946,04 €
3	2,8	1.519,77 €	5,6	455,93 €	-4.582,36 €	2.226,22 €	2.073,33 €	-9.872,71 €
4	2,8	1.556,25 €	5,6	466,87 €	-4.692,34 €	2.279,65 €	2.073,33 €	-7.799,38 €
5	2,8	1.593,60 €	5,6	478,08 €	-4.804,95 €	2.334,36 €	2.073,33 €	-5.726,05 €
6	2,8	1.631,84 €	5,6	489,55 €	-4.920,27 €	2.390,39 €	2.073,33 €	-3.652,71 €
7	2,8	1.671,01 €	5,6	501,30 €	-5.038,36 €	2.447,76 €	2.073,33 €	-1.579,38 €
8	2,8	1.711,11 €	5,6	513,33 €	-5.159,28 €	2.506,50 €	2.073,33 €	493,95 €
9	2,8	1.752,18 €	5,6	525,65 €	-5.283,10 €	2.566,66 €	2.073,33 €	2.567,28 €
10	2,8	1.794,23 €	5,6	538,27 €	-5.409,90 €	2.628,26 €	2.073,33 €	4.640,62 €
11	0	1.837,29 €	5,6	551,19 €	-5.539,73 €	-2.453,08 €	-1.889,79 €	2.750,83 €
12	0	1.881,39 €	2,8	564,42 €	-2.836,34 €	-1.255,98 €	-944,89 €	1.805,94 €

Table 7.2.II.- Cash flows for sale rates of 2,8 annual licences.

With the half of the sales, it is necessary the double of the incomes; thus it is quite clear that the curve of offer must be of the type: Price=517,63€/unit.

7.3. INVESTMENT ECONOMIC PARAMETERS

Following the curve of offer previously indicated, the main investment economic parameters are calculated:

Lifetime [years]	NPV [€]	IRR [%]	PPI [años]
12	1.805,99 €	5,0%	7,8

Table 7.3.I.- Economic parameters for the investment in a consumption estimation modelling software.

It is a very risky investment because the behaviour of the potential clients is not known, and thus, the IRR cannot be well calculated.

8. HYDRAULIC TURBINES

The self – generation possibilities for tunnels are real and even some previous experiments are already known.

One of the possible energy sources for the self – generation is the hydraulic energy, as the water that flows through the drainage pipes has some potential energy. However, its characteristics are quite different among different tunnels, being even negative in the case of tunnels under the phreatic level.

As part of the task T4.7 within the WP4, a water flow measuring device is installed in the Folgoso tunnel aimed at determining how the water flow from drainage varies under external conditions and also estimating the real capacity for energy generation throughout a whole year.

The drainage system in the Folgoso tunnel pours the captured water behind the support structure in the Uma River, through the pipe shown in the **Figure 8.I.**

Figure 8.I.- Discharge point in the Uma River.

In order supervise permanently the drainage water flow, the system shown in the **Figure 8.II** is installed, which, thanks to the ultrasound use, can measure and register the water height in the inside of the pipe.

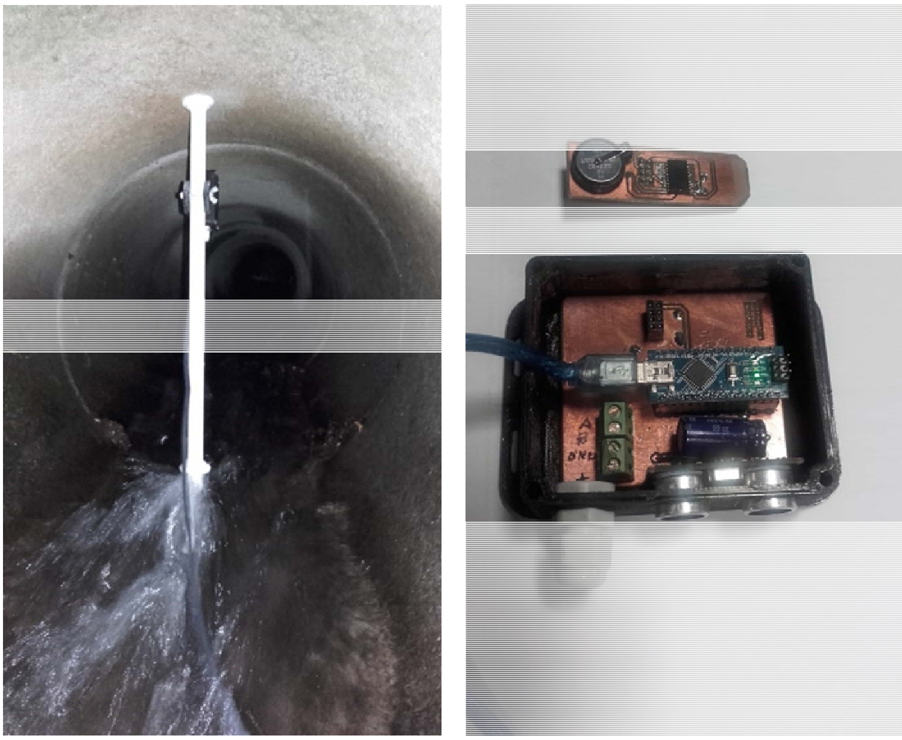

Figure 8.II.- Placement of the height registration unit.

Just in the exit of the pipe a box is put in place with an exit shaped in V, whose 3D model is shown in the **Figure 8.III**. The aperture of the sheet steel is designed in order to establish a relation between the outlet water flow and the water level height under supervision.

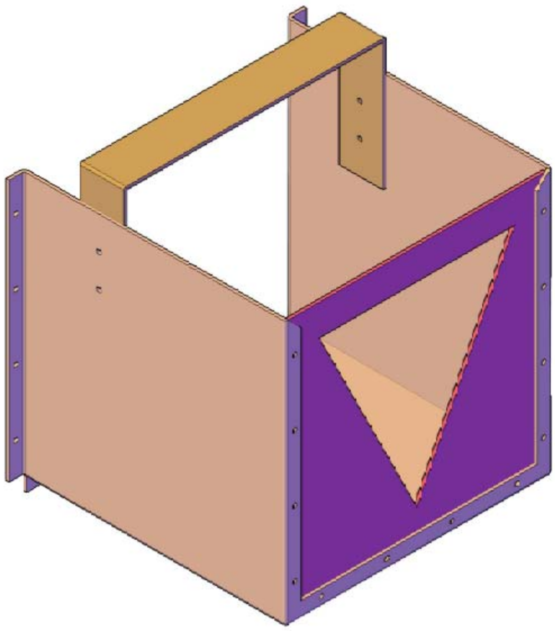

Figure 8.III.- Profile for the determination of the levels.

With the aid of this system, the height of the water flow is registered each minute throughout 42 days, obtaining the results shown in the **Figure 8.IV**. Once the formula that establishes the relation between height and water flow is applied, the average water flow obtained is around 16,07 l/s and 26,79 l/s.

The points with lack of continuity at the registrations 9.000 and 21.000 are due to the power outage in the general power supply of the tunnel.

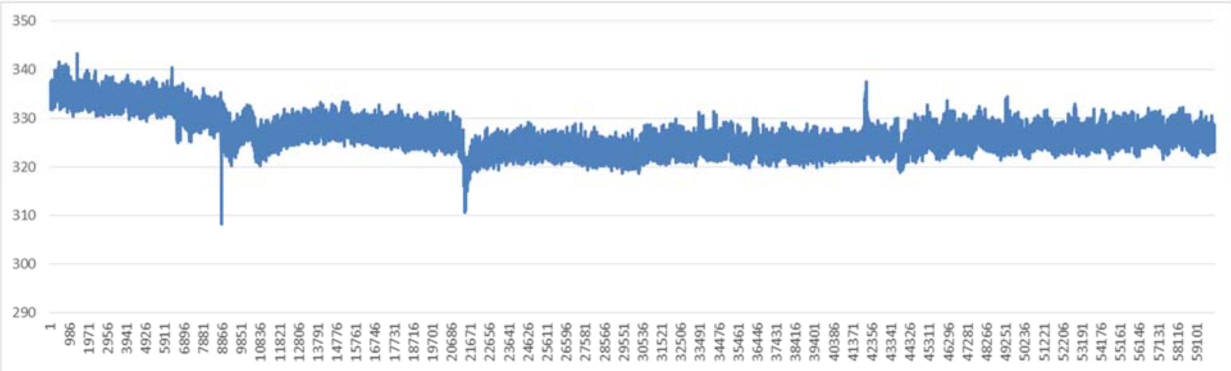

Figure 8.IV.- Variation of the water flow height throughout the time.

In the **Figure 8.V** it is compared the variation of the rainfall in the zone (blue colour) with the variation of the height of the drained water flow (red colour) during 44 days of registrations, without achieving to establish a correlation between both of them.

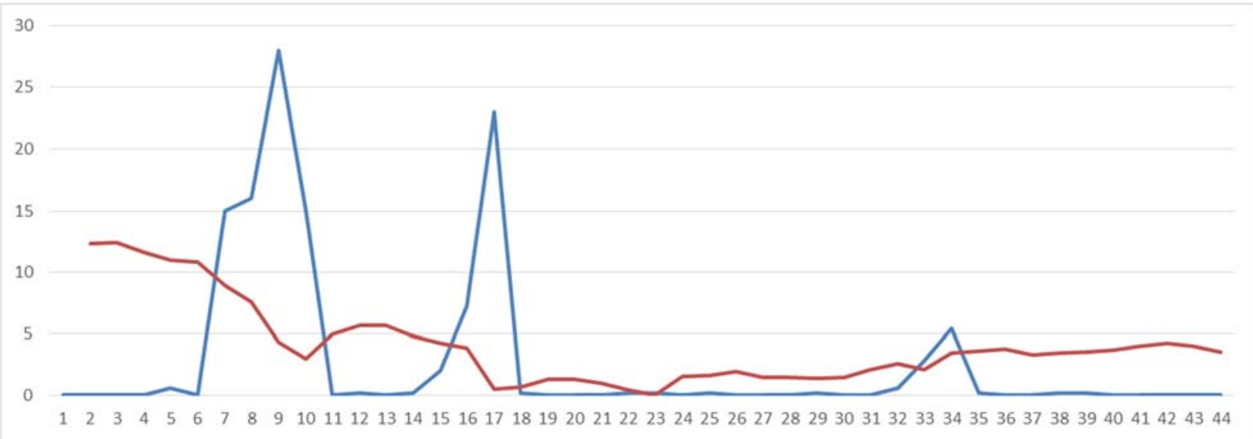

Figure 8.V.- Variation in the water flow height (blue colour) with respect to rainfall (red colour).

Since no explanation has been found for the variation in the water flow, from now on this report will use the average water flow (21,43 l/s).

The available height for potential energy is just 0,5m, but due to the cartography of the environment, this can easily incremented to 3m if the point of capture and discharge of the water is not the same.

The available power as hydraulic energy in the Folgoso tunnel can be obtained as the product of the water flow, the gravity, the water density and the available height, which turns out to be P=0,02143*9,8*1000*3= 636,47 W.

From the available 636W, a 30% will be lost in the turbine and another 10% will be lost in the electric generator, reaching a power of 400W.

Taking into account that the minimum power consumed by the tunnel is 75W, it is quite evident that the implantation of a turbines system doesn't lead to a significant power increase.

There are other tunnels, especially in high mountains, where the topography allows bigger heights of fall and also high water flows, which are generated in melting seasons. However, in this case, it should be more correct to point out that the hydroelectric turbines system to install would be placed in the tunnel's environment rather than in the inside of the tunnel.

9. MICRO WIND GENERATORS

This system is quite known since several years and the precedent of this generator was the windmill used for the flour process.

The wind energy is getting more and more popular currently, since it has demonstrated the industrial viability. In its origins, it appeared as an alternative to the conventional electric generation with fossil fuels.

For the tunnels' domain, due to space limitations, it must be employed wind generators with a power below 100 kW, getting into the mini wind energy.

The wind arriving at a wind generator blades has a kinetic power equal to:

$$E = \frac{1}{2} m v^2$$

Where v is the wind's velocity and m is the air mass considered.

The power is calculated through a derivation with respect to the time, at a constant speed, giving the following result:

$$\frac{dE}{dt} = \frac{1}{2} \frac{dm}{dt} v^2$$

The mass flow is equal to:

$$\frac{dm}{dt} = \rho A \frac{dx}{dt} = \rho A v$$

Where ρ is the air density and A is the cross sectional area occupied by the blades.

Then, the definitive available power will be given by:

$$P_{el} = \frac{1}{2}\rho A v^3$$

As it has been indicated in the document **DELIVERABLE_D3.1**, the velocity in the Bielsa tunnel has been studied, with the aid of five anemometers. The summary of the statistical treatment is shown in the following table:

	Daytime		**Night time**	
Month	Percentile	% useful time	Percentile	% useful time
nov-13	76	24,00%	75,6	24,40%
dec-13	100	0,00%	100	0,00%
jan-14	80,5	19,50%	84,8	15,20%
feb-14	-	-	-	-
mar-14	95,5	4,50%	80,2	19,80%
apr-14	99,6	0,40%	99,3	0,70%
may-14	92	8,00%	93,7	6,30%
jun-14	100	0,00%	99,8	0,20%
Jul-14	99,8	0,20%	99,4	0,60%
aug-14	95,6	4,40%	99,1	0,90%
sep-14	100	0,00%	100	0,00%
oct-14	99,5	0,50%	97,6	2,40%

Table 9.I. – Statistical results of the filtered data.

It will be considered aero generators with a blades surface of 1m2 and the air density constant and equal to 1,25 kg/m^3.

$$P_{el} = \frac{1}{2} * 1{,}25 * 1 * v^3 = 0{,}75 * v^3$$

By the integration of the power through the month of December, obtained as a function of the average air velocity, measure experimentally and dividing it by the integration time, it can be obtained the available average power per m2, with a value of 79,37 W.

The Bielsa tunnel has a cross sectional area of 35,6 m2; then, it has a potential to generate 79,37*35,6 = 2.826 W = 2,8 kW.

From the 2,8 kW of available wind energy, a 45% will be lost in the blades and a 10% will be lost in the electric generator, with a final power that turns out to be 1,4 kW.

According to these data, the Bielsa tunnel's capacity for wind energy generation is higher than the hydraulic generation capacity in the Folgoso tunnel, but it remains to be a very small amount.

Unlike what happened with the hydraulic generation capacity, which remained practically constant throughout the time, the wind energy generation has strong availability variations, which forces the equipment to be oversized with respect to the average generation value and, thus, more expensive.

10. ASPHALT PIEZO ELECTRIC GENERATOR

The idea is to take advantage of a phenomenon known since several decades, the piezo electricity, for its application in the roads domain, achieving that the vehicles circulating generate electricity.

The piezo electricity is a phenomenon based on some glasses that, after being submitted to mechanical tensions (pressure), acquire an electric polarisation in its mass, in such a way that it appears a potential difference and electrical charges on its surface.

This element is an authentic innovation, although as in the case of many others, it is not based on a completely new invention, but on the application of a principle, which is well established by the science for a finality not expected so far.

Since several years, the research on these devices has oriented towards the electricity generation, thanks to the traffic passing on the road, which creates a pressure on the road that can be used.

10.1. SYSTEM'S OPERATION

First of all, a portion of the road must be chosen and then, the asphalt piezo electric generators must be put in place under the asphalt with an adequate depth. These elements must be at a distance of 3cm from the asphalt surface, but the group of elements of the generator needs more space, then the ditch for their placement must be deeper.

Some cables come from the generators and connect with some batteries that are placed close to the road. When the vehicles transit over the road, they activate the generators that convert the mechanical energy from the pressure of the wheels into electrical energy.

The generated energy is stocked in the batteries. This energy that is accumulated can be used for local needs or can be redirected to the electric mesh.

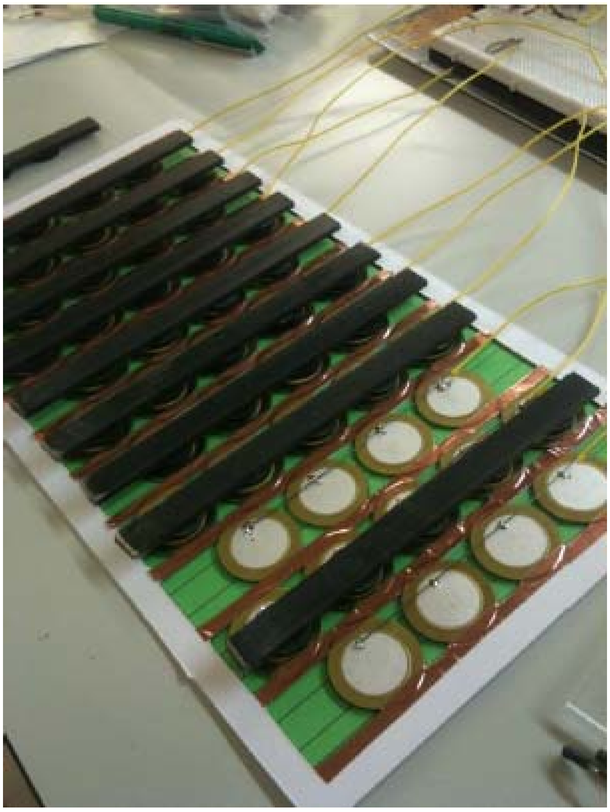

Figure 10.1.l.- Matrix of piezo electric generators.

10.2. ADVANTAGES THAT THIS SYSTEM WOULD PROVIDE

The energy would be generated and consumed in the same space with no need or transportation, which constitutes the source of many losses; in second place, but not with less importance, this system possesses a great potential depending on the covered surface and the traffic rate.

The maintenance has to be taken into account: it has to be pointed out in this sense that generators can have a lifetime of 30 years and, besides, due to the fact that they are placed below the surface, they are not exposed to vandalism acts.

Finally, it has to be added that, unlike what happens with other infrastructures, the landscape would not be altered.

10.3. CALCULATION OF THE INVESTMENT COST

In order to calculate the investment cost of the system, it has to be studied the material and implantation cost of the elements of the whole system. These cost of the installation of the main elements are shown in the following table for a 1 km – length tunnel.

INVESTMENT COST				
Concept	**Unit**	**Measure**	**Unit Price**	**Total price**
Asphalt piezo electric boxes	unit	1000	621,25	621.250,00
Charging batteries	unit	2	1.425,12	2.850,24
Inverters	unit	2	18.833,37	37.666,74
Cables	m	2500	0,77	1.925,00
Milling	m3	180	4,50	810,00
Irrigation adhesion	m2	3600	0,25	900,00
Bituminous mixture	T	436,8	54,80	23.936,64
			TOTAL	689.338,62

Table 10.3.I.- Initial investment for the asphalt piezo electric generator on a road.

Currently, the cost for the installation of this system on the road is around 690.000 € per kilometre.

10.4. ENERGY GENERATION ESTIMATION

In October 2009, a test was carried out in a 10m portion of road on the Road 4 on the north of Hadera (Israel). This is the first practical test of the entire system developed by Innowatech, in association with Technion (Israeli Technology Institute). The pilot test was launched in cooperation with the National Israeli Road Company. The system includes IPEGs ™ (Innowattech Piezo Electric Generators), a gathering module and a battery.

During the pilot test, the IPEGs were placed at a depth of 5cm below the asphalt layer, in order to produce 2000 Wh of energy on average on that portion of the road.

The extension of this project to a new length of one kilometre over a lane would be enough to produce an average of 200 kWh if 600 Heavy Goods Vehicles (HGV) or buses travelled on this location. The traffic rate and the characteristics of that traffic are key factors for this way of energy generation. In any case, it is clear that it is predictable that the amount of energy created in a metropolitan area will be higher than out of a city.

With these data, gathered thanks to the tests done by Innowatech, it has been obtained a curve dependant on the traffic in such a way that if 600 HGV provide 200 kWh of energy, a quarter of this amount of energy can be produced with light vehicles.

The calculations show that every asphalt piezo electric box installed provides an amount of energy of 0,08325 Wh when a lorry passes.

10.5. CALCULATION OF THE CASH FLOWS

In order to determine the cash flows that the system is able to generate, it has to be taken into account the amount of energy that the system produces throughout several years has to be multiplied by the price of the kWh during this period of time.

It has to be determined the energy that the generator is able to produce thanks to the piezo electric effect. For this purpose and thanks to all the data that have been gathered, it is determined the annual power as a function of the traffic intensity registered on a road.

On the other hand, it has been estimated that the exploitation and maintenance costs for this system will be of a 0,5% of the system’s implementation value during the first five years, increasing another 0,5% every five years till the end of the system’s lifetime.

It is shown in the following lines, several examples of annual cash flows according to the existing traffic rate; a first example with a daily traffic rate rather high, the second one with a medium traffic rate and the third one with a low traffic rate.

The first example is relative to the *Calzadas Superpuestas* tunnel, which has a very high traffic rate and it is placed in the outskirts of the city of Madrid; its length is 1.004 meters, with 14.330 vehicles per day and per lane with a 3,94% of Heavy Goods Vehicles (HGV).

It has been assumed that this installation is placed just in the slow lane, because HGV must transit always on this lane, unless an unexpected fact happens.

CASH FLOWS						
Year	€/KWh	Generation [kWh]	Maintenance [€]	Cash flow	Cash flow at year 0	Accumulated
0	0,1217583	0	0,00 €	-692.095,97 €	-692.095,97 €	-692.095,97 €
1	0,12516513	487.391	-3.460,48 €	57.543,85 €	56.195,16 €	-635.900,81 €
2	0,12866728	487.391	-3.460,48 €	59.250,77 €	56.505,93 €	-579.394,88 €
3	0,13226743	487.391	-3.460,48 €	61.005,44 €	56.815,75 €	-522.579,13 €
4	0,13596831	487.391	-3.460,48 €	62.809,22 €	57.124,65 €	-465.454,48 €
5	0,13977274	487.391	-3.460,48 €	64.663,46 €	57.432,69 €	-408.021,79 €
6	0,14368362	487.391	-6.920,96 €	63.109,11 €	54.738,43 €	-353.283,36 €
7	0,14770392	487.391	-6.920,96 €	65.068,57 €	55.115,22 €	-298.168,14 €
8	0,15183672	487.391	-6.920,96 €	67.082,85 €	55.489,64 €	-242.678,51 €
9	0,15608515	487.391	-6.920,96 €	69.153,50 €	55.861,75 €	-186.816,75 €
10	0,16045245	487.391	-6.920,96 €	71.282,08 €	56.231,65 €	-130.585,10 €
11	0,16494196	487.391	-10.381,44 €	70.009,75 €	53.933,55 €	-76.651,56 €
12	0,16955708	487.391	-10.381,44 €	72.259,11 €	54.361,72 €	-22.289,84 €
13	0,17430133	487.391	-10.381,44 €	74.571,42 €	54.786,43 €	32.496,58 €
14	0,17917833	487.391	-10.381,44 €	76.948,42 €	55.207,79 €	87.704,37 €
15	0,18419178	487.391	-10.381,44 €	79.391,94 €	55.625,90 €	143.330,27 €
16	0,18934552	487.391	-13.841,92 €	78.443,34 €	78.443,34 €	221.773,61 €
17	0,19464346	487.391	-13.841,92 €	81.025,50 €	79.126,47 €	300.900,08 €
18	0,20008963	487.391	-13.841,92 €	83.679,92 €	79.803,39 €	380.703,47 €
19	0,2056882	487.391	-13.841,92 €	86.408,61 €	80.474,29 €	461.177,76 €
20	0,21144341	487.391	-13.841,92 €	89.213,64 €	81.139,34 €	542.317,09 €

Table 10.5.I.- Cash flows of the asphalt piezo electric generator for the *Calzadas Superpuestas* tunnel.

The second case studies the Bruc tunnel (in the Barcelona province) in the A2 highway, with a 1.100m length, a traffic rate of 7.001 vehicles per day and per lane and 23,09% of HGV rate.

CASH FLOWS						
Year	€/KWh	Generation [kWh]	Maintenance [€]	Cash flow	Cash flow at year 0	Accumulated
0	0,1217583	0	0,00 €	-758.272,48 €	-758.272,48 €	-758.272,48 €
1	0,12516513	360.456	-3.791,36 €	41.325,10 €	40.356,54 €	-717.915,94 €
2	0,12866728	360.456	-3.791,36 €	42.587,47 €	40.614,58 €	-677.301,36 €
3	0,13226743	360.456	-3.791,36 €	43.885,16 €	40.871,24 €	-636.430,12 €
4	0,13596831	360.456	-3.791,36 €	45.219,17 €	41.126,59 €	-595.303,53 €
5	0,13977274	360.456	-3.791,36 €	46.590,49 €	41.380,67 €	-553.922,86 €
6	0,14368362	360.456	-7.582,72 €	44.208,83 €	38.345,05 €	-515.577,81 €
7	0,14770392	360.456	-7.582,72 €	45.657,97 €	38.673,81 €	-476.904,00 €
8	0,15183672	360.456	-7.582,72 €	47.147,66 €	38.999,63 €	-437.904,37 €
9	0,15608515	360.456	-7.582,72 €	48.679,03 €	39.322,61 €	-398.581,77 €
10	0,16045245	360.456	-7.582,72 €	50.253,25 €	39.642,82 €	-358.938,94 €
11	0,16494196	360.456	-11.374,09 €	48.080,15 €	37.039,60 €	-321.899,34 €
12	0,16955708	360.456	-11.374,09 €	49.743,70 €	37.423,00 €	-284.476,34 €
13	0,17430133	360.456	-11.374,09 €	51.453,79 €	37.802,27 €	-246.674,07 €
14	0,17917833	360.456	-11.374,09 €	53.211,73 €	38.177,54 €	-208.496,52 €
15	0,18419178	360.456	-11.374,09 €	55.018,86 €	38.548,92 €	-169.947,60 €
16	0,18934552	360.456	-15.165,45 €	53.085,19 €	53.085,19 €	-116.862,41 €
17	0,19464346	360.456	-15.165,45 €	54.994,86 €	53.705,92 €	-63.156,49 €
18	0,20008963	360.456	-15.165,45 €	56.957,97 €	54.319,35 €	-8.837,14 €
19	0,2056882	360.456	-15.165,45 €	58.976,00 €	54.925,68 €	46.088,53 €
20	0,21144341	360.456	-15.165,45 €	61.050,50 €	55.525,10 €	101.613,64 €

Table 10.5.II.- Cash flows of the asphalt piezo electric generator in the Bruc tunnel.

For the third case, it is chosen for the comparison the Folgoso tunnel, which has a length of 2.500m, a traffic rate of 3.748 vehicles per day and per lane and 17,19% of HGV rate.

CASH FLOW						
Year	€/KWh	Generation [kWh]	Maintenance [€]	Cash flows	Cash flows at year 0	Accumulated
0	0,1217583	0	0,00 €	-1.723.346,55 €	-1.723.346,55 €	-1.723.346,55 €
1	0,12516513	172.792	-8.616,73 €	13.010,84 €	12.705,90 €	-1.710.640,65 €
2	0,12866728	172.792	-8.616,73 €	13.615,99 €	12.985,22 €	-1.697.655,43 €
3	0,13226743	172.792	-8.616,73 €	14.238,06 €	13.260,23 €	-1.684.395,20 €
4	0,13596831	172.792	-8.616,73 €	14.877,55 €	13.531,05 €	-1.670.864,15 €
5	0,13977274	172.792	-8.616,73 €	15.534,92 €	13.797,78 €	-1.657.066,37 €
6	0,14368362	172.792	-17.233,47 €	7.593,96 €	6.586,71 €	-1.650.479,66 €
7	0,14770392	172.792	-17.233,47 €	8.288,64 €	7.020,75 €	-1.643.458,91 €
8	0,15183672	172.792	-17.233,47 €	9.002,75 €	7.446,90 €	-1.636.012,00 €
9	0,15608515	172.792	-17.233,47 €	9.736,85 €	7.865,37 €	-1.628.146,64 €
10	0,16045245	172.792	-17.233,47 €	10.491,49 €	8.276,32 €	-1.619.870,32 €
11	0,16494196	172.792	-25.850,20 €	2.650,51 €	2.041,88 €	-1.617.828,44 €
12	0,16955708	172.792	-25.850,20 €	3.447,96 €	2.593,96 €	-1.615.234,48 €
13	0,17430133	172.792	-25.850,20 €	4.267,73 €	3.135,44 €	-1.612.099,04 €
14	0,17917833	172.792	-25.850,20 €	5.110,44 €	3.666,56 €	-1.608.432,48 €
15	0,18419178	172.792	-25.850,20 €	5.976,73 €	4.187,59 €	-1.604.244,89 €
16	0,18934552	172.792	-34.466,93 €	-1.749,48 €	-1.749,48 €	-1.605.994,37 €
17	0,19464346	172.792	-34.466,93 €	-834,04 €	-814,49 €	-1.606.808,86 €
18	0,20008963	172.792	-34.466,93 €	107,02 €	102,06 €	-1.606.706,79 €
19	0,2056882	172.792	-34.466,93 €	1.074,41 €	1.000,62 €	-1.605.706,17 €
20	0,21144341	172.792	-34.466,93 €	2.068,87 €	1.881,62 €	-1.603.824,55 €
21	0,21735965	172.792	-43.083,66 €	-5.525,58 €	-4.907,70 €	-1.608.732,25 €
22	0,22344143	172.792	-43.083,66 €	-4.474,70 €	-3.881,18 €	-1.612.613,43 €
23	0,22969338	172.792	-43.083,66 €	-3.394,41 €	-2.875,18 €	-1.615.488,61 €
24	0,23612027	172.792	-43.083,66 €	-2.283,89 €	-1.889,19 €	-1.617.377,80 €
25	0,24272697	172.792	-43.083,66 €	-1.142,31 €	-922,75 €	-1.618.300,55 €
26	0,24951854	172.792	-51.700,40 €	-8.585,51 €	-6.772,77 €	-1.625.073,32 €
27	0,25650014	172.792	-51.700,40 €	-7.379,14 €	-5.684,68 €	-1.630.758,01 €
28	0,26367708	172.792	-51.700,40 €	-6.139,02 €	-4.618,49 €	-1.635.376,49 €
29	0,27105483	172.792	-51.700,40 €	-4.864,20 €	-3.573,65 €	-1.638.950,14 €
30	0,27863902	172.792	-51.700,40 €	-3.553,71 €	-2.549,66 €	-1.641.499,81 €

Table 10.5.III.- Cash flows for the asphalt piezo electric generator in the Folgoso tunnel.

10.6. INVESTMENT ECONOMIC PARAMETERS

The main investment economic parameters are calculated for the three studied tunnels:

Tunnel	Lifetime [years]	NPV [€]	IRR [%]	PPI [años]
Calzadas Superpuestas	30	967.879,40 €	9,5%	12,4
El Bruc	30	386.867,92 €	5,4%	18,2
Folgoso	30	-1.629.735,74 €	--	--

Table 10.6.I.- Economic parameters for the investment in the three tunnels.

The results show that the return of the investment is subject to the traffic rate, not being any more interesting for tunnels with a traffic rate below the Bruc tunnel's one (7.000 vehicles per day and per lane).

11. CONCLUSIONS

The **Table 11.I** outlines the global results of the viability study that has been done on this report.

Task	Measure	Lifetime [years]	NPV [€]	IRR [%]	PPI [años]	Remarks
T4.1	Wireless tunnel	--	--	--	--	Unprofitable
T4.2	Lighting permanent control	--	--	--	--	Unprofitable
T4.3	Total On-Off control of the lighting system	20	21.646,66 €	16,50%	6,8	Not under standard or law
	Partial On-Off control of the lighting system		7.788,29 €	9,40%	10,8	Not under standard or law
T4.4	Profitability of the external luminosity	25	808.574,70 €	10,30%	11,1	
T4.5	Consumption database in real time	15	4.595,06 €	7,20%	10,6	
T4.6	Computational consumption model	12	1.805,99 €	5,00%	7,8	
T4.7	Hydraulic turbines	--	--	--	--	Negligible efficiency
T4.8	Micro-wind turbine	--	--	--	--	Negligible efficiency
T4.9	Asphaltic piezo electric generator	30	967.879,40 €	9,50%	12,4	In tunnels with high traffic rate

Table 11.I.- Resumen de estudios de viabilidad.

Among the energy efficiency measures, the one that has the best IRR is the On-Off control of the lighting system, but it has to be ruled out, since it wouldn't verify the current standards.

The energy efficiency measure with the second best IRR is the profitability of the external luminosity, which is an innovative measure from which no technical documentation is available; for this reason, it will be necessary to develop scale models to estimate rates of consumption and system’s efficiencies.

The task relative to the development of a prototype for the profitability of the external luminosity will be carried out in the WP5.

In the WP4 it has been verified that the increase in the energy efficiency in the tunnels domain can be achieved through the reduction of the installations consumption or through the profitability of the energy sources associated to the tunnel.

Within the wide range of available installation in the tunnels, it is important to reduce the consumption or improve the efficiency of the lighting system, since it is the one with higher energy needs to be covered.

The LED lighting offers a wide range of alternatives with respect to the consumption reduction because, it doesn’t just have a good efficiency, but it also allows a linear regulation and almost instantaneous response, opening the door to intelligent lighting systems able to adapt their operation to the traffic conditions, even switching off the installation when they are not required. However, the implementation of this sort of intelligent behaviours depend strongly on the lighting standards being updated regularly, in such a way that the new lighting alternatives can be assessed in the law framework.

In general, the energy self – generation has turned out to be not viable because of the small amount of created energy in comparison with the tunnel’s total consumption. It only seems to be of interest the asphalt piezo electric generation in tunnels with high traffic rate, but this measure doesn’t have to be restricted to tunnels; in fact, its implantation seems to be easier in open-air roads.

The profitability of the external luminous energy can be considered as an alternative to the self – generation, measure that seems to be of great interest, since the required luminous energy in the inside of the tunnel is much less than the one available in the exterior.

The profitability of the external luminous energy is not only technically interesting, but it constitutes as well an innovative measure and presents the second best IRR (Internal Rate of Return) among the group of studied measures, that’s why this option is chosen for the development of the prototype in the WP5 framework.

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