IMPROVING ENERGY EFFICIENCY IN ROAD TUNNELS

[1]Lorenz Kirchebner, [1]Alexander Wierer, [2]Christof Sistenich, [3]Michael Bacher, [3]Marlene Hinterhofer, [4]Thomas Marcher, [4]Georg Kaml

[1]crypta.sec conceptum GmbH, AT
[2]BASt, Federal Highway and Transport Research Institute, DE
[3]Graz University of Technology, Institute of Thermodynamics and Sustainable Propulsion Systems, AT
[4]Graz University of Technology, Institute of Rock Mechanics and Tunnelling, AT

DOI 10.3217/978-3-99161-087-8-029 (CC BY-NC 4.0)

ABSTRACT

The operation of road tunnels leads to considerable energy costs, which are expected to increase further due to the rising energy prices and stricter climate policies. This elaboration highlights technical, operation and planning-based approaches to reduce energy demand and life-cycle costs, based on the findings of the BASt research project “Ermittlung und Bewertung zur Steigerung der Energieeffizienz”.

Energy consumption data from more than 35 road tunnels have been analyzed, revealing that lighting accounts for the largest share – 50 % to 60 % – of the total energy demand, consistent with findings across the DACH region (Germany, Austria and Switzerland). Based on these insights, the project identifies three main pillars for energy optimization:

- Energy sources near or within the tunnel: integration of renewable energy systems, such as photovoltaic panels, hydropower from drainage systems and electricity generation from natural airflows
- Energy saving measures: implementation of energy-efficient components and design strategies, including optimized tunnel portals, high-reflectivity road surfaces and daylight-introducing elements like entrance light shafts
- Operation strategies: improves system control and regular maintenance, such as adaptive lighting control, demand-based ventilation control and implementation of energy monitoring with benchmark integration

Beyond technical measures a methodical framework for assessing tunnel energy performance as a basis for systematic energy management is developed. These results contribute to the development of a practical planning tool that supports sustainable tunnel operation and energy-efficient infrastructure design.

Keywords: Energy efficiency, sustainable tunnel operation, energy monitoring, energy management, energy-reducing measures

1. INTRODUCTION

Energy efficiency has become a central concern in the planning and operation of road tunnels. The continuous operation of lighting, ventilation and safety systems leads to a substantial energy demand and operating costs, which are expected to increase further due to increasing energy prices and ambitious climate and carbon neutrality targets like the European directive [1] and energy efficiency reform act in Austria [2]. Nevertheless, energy consumption has historically been neglected in design and operation.

To address this need the „Bundesanstalt für Straßen- und Verkehrswesen (BASt)“ initiated the research project „Ermittlung und Bewertung von Maßnahmen zur Steigerung der Energieeffizienz von Straßentunneln bei Planung und Betrieb (FE 15.0705/2022/ERB)“. The project was funded by the „Bundesministerium für Digitales und Verkehr (BMDV)“ and conducted in cooperation with tunnel operators and planners. Its objectives were:

- To establish a comprehensive understanding of energy flows in road tunnels and their dependency on design and operation parameters
- To identify and evaluate energy-saving measures and renewable energy integration options
- To develop a practical energy management framework for both existing tunnels and new constructions
- To provide decision support and planning tools enabling operators and planners to balance safety, functionality and energy efficiency

The methodological approach in the project combined theoretical, empirical and computational elements. A literature review and regulatory analysis (e.g. RE-ING [3], RVS [4]) established the boundary conditions for tunnel equipment and operation. Real energy consumption data from over 35 German tunnels were collected and normalized to ensure comparability between tunnels with different length, geometry and equipment levels. Complementary simulation models were used to estimate energy demand and evaluate substitution potentials. The results formed the foundation for a structured catalogue of efficiency measures, grouped into technical, operation and strategic categories.

This paper provides an overview of the projects’ key content and results. The main focus is on the structure and applicability of energy management, its operational implementation in planning practice and the derivation of relevant measures to reduce energy consumption in tunnel operations.

2. ENERGY DEMAND AND CONSUMPTION CHARACTERISTICS

2.1. Installed Power vs. Operational Consumption

Energy demand in road tunnels is defined by the total installed electrical power of the installed subsystems. However, actual energy consumption is primarily governed by operation control, external conditions and system usage.

Ventilation systems typically represent the largest portion of installed power (up to 80 %, **Figure 1**) but their actual energy consumption often remains below 10 % of the total energy consumption (**Figure 2**) – full-load operation occurs only during maintenance or emergency scenarios. In contrast, lighting systems – especially entrance and transitions zones – show continuous operation making them the dominant consumer in daily tunnel operation (**Figure 2**).

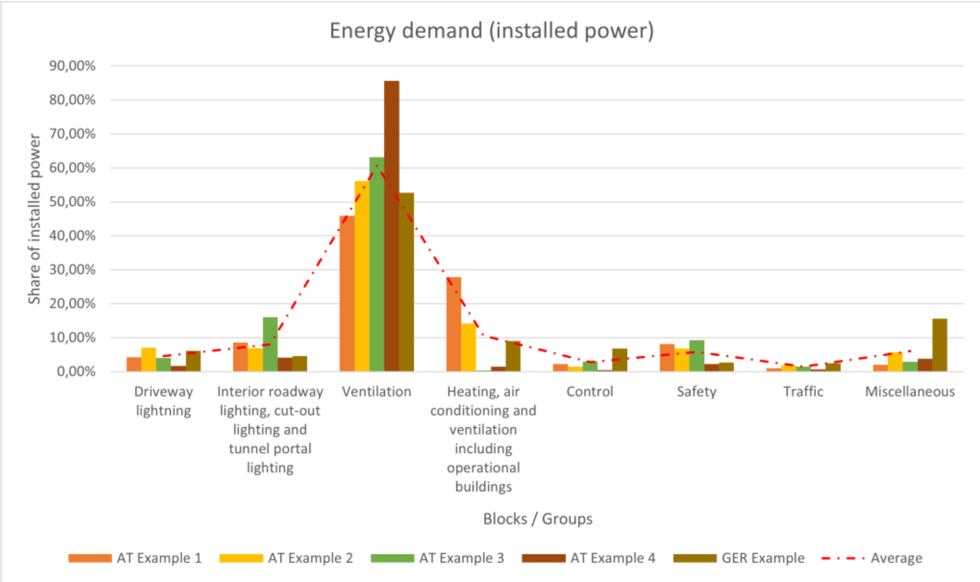

Figure 1: Example installed power of five tunnel systems.

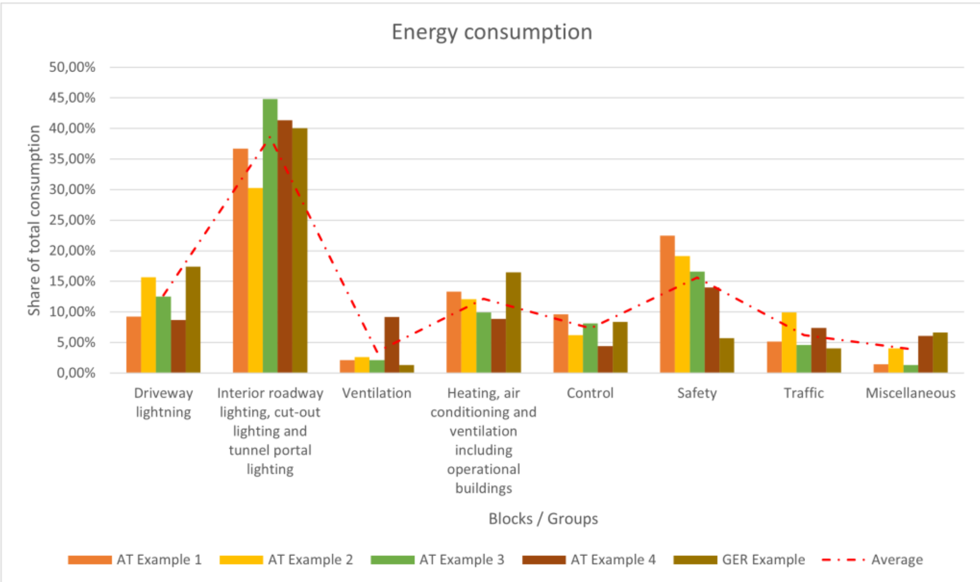

Figure 2: Example consumption of the same five tunnel systems.

The energy demand of tunnel systems fluctuates seasonally and diurnally. Lighting demand is directly linked to external luminance, which varies with weather, season and geographic orientation of the portals. On the other hand, ventilation demand depends on traffic load, air quality thresholds and control strategies.

This imbalance in **Figure 1** and **Figure 2** underlines the necessity for measurement-based energy assessment rather than relying solely on installed power. Furthermore, it becomes clear that significant savings can be achieved through operational optimization without the need to replace major hardware.

3. ENERGY CONSUMPTION IN THE DACH-REGION

The DACH comparison (Germany, Austria and Switzerland) provides insights into structural and operational factors influencing tunnel energy use. The analysis covered tunnels from Germany (38), Austria (51) and Switzerland (35) with a wide variety of different tunnel types (direction of traffic, ventilation system, length, number of bores, etc.).

3.1. Comparative Energy Distribution

For a direct comparison one single-way tunnel with longitudinal ventilation was compared for each country in the DACH region. Energy consumers were divided into similar groups. Normalized energy data (kWh per lane-meter) showed a consistent dominance of lighting energy in all three countries with shares ranging between 50 % and 60 % of total consumption, as seen in **Figure 3**.

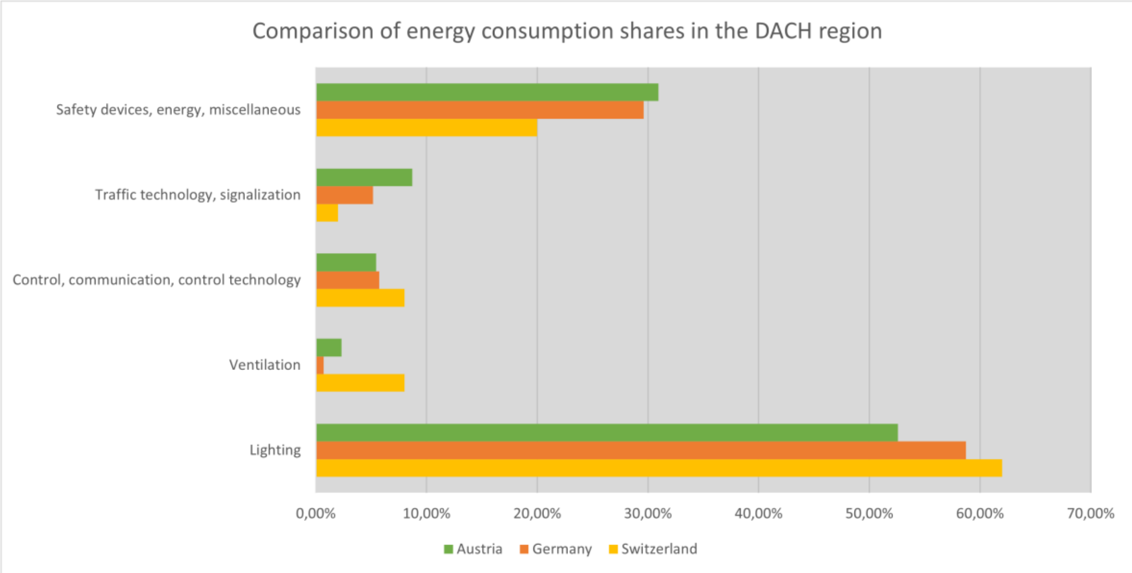

Figure 3: Comparison of energy consumption shares in the DACH region

Differences between countries are mainly attributed to design standards and lighting concepts. Austrian tunnels employ shorter entrance zones and lower luminance levels under dry conditions while Germany and Switzerland dimension for wet pavement reflections and apply symmetric lighting resulting in higher average energy demand.

4. ENERGY MANAGEMENT FRAMEWORK

The developed framework defines a systematic approach to record, evaluate and improve energy performance in tunnel operation. It consists of two interconnected levels:

- Strategic Energy Planning Aid
- Operational Planning Aid

4.1. Strategic Energy Planning Aid

The strategic guide provides the organizational and regulatory foundation for energy management. It defines responsibilities and procedures for energy-related decisions. Key elements include:

- Definition of an energy policy at operator level
- Identification of legal and economic boundary conditions
- Assessment of potential renewable energy sources near the tunnel site
- Integration of energy criteria into design and procurement processes
- Role of the electricity energy mix
- Importance of planning cycles, tendering models and make-or-buy decisions

4.2. Operational Planning Aid

At the operational level, energy management focuses on monitoring, analysis and optimization. The key steps are:

- Energy flow analysis: identification of main consumers and efficiency bottlenecks
- Energy performance indicators: development of comparable metrics
- Benchmarking: comparison against similar tunnels to identify outliers
- Evaluation: assessment of potential savings, costs and life-cycle developments
- Visualization: visual representation and its advantage of the energy flow within the tunnel
- Measures: selection of suitable measures to increase energy efficiency and reduce energy consumption

This framework supports operators in prioritizing investments and ensures that energy efficiency becomes a continuous and verifiable management process rather than a one-time action.

5. CATALOGUE OF ENERGY EFFICIENCY MEASURES

A detailed catalogue of measures was developed within the project to support practical implementation. It groups individual measures in three key pillars for increasing the efficiency of road tunnels (**Figure 4**).

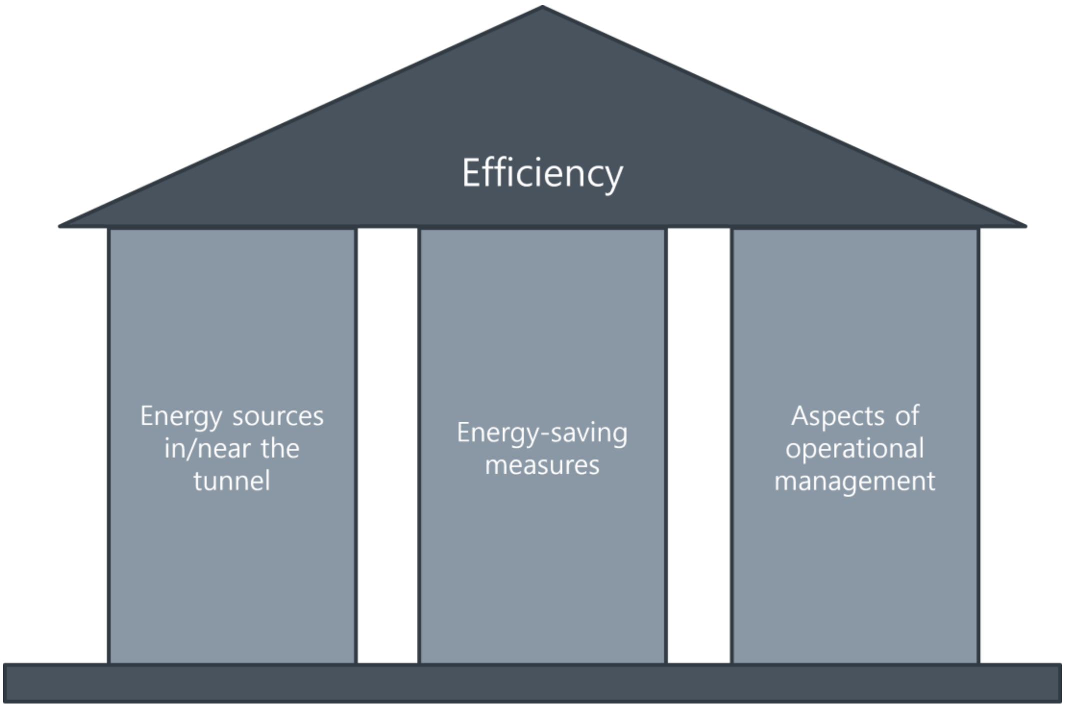

Figure 4: Key pillars for increasing the efficiency of road tunnels

The three main categories include the following measures (**Table 1**).

Table 1: Categories and analyzed measures

Category	Measures
EQ – Energy sources [5], [6], [7], [8], [9], [10], [11], [12], [13]	Generation of electrical energy from air currents in tunnels using meteorological portal pressure differences and buoyancy currents
	Geothermal energy – absorber tubes
	Geothermal energy – combination of open system with absorber tubes
	Geothermal mountain water utilization
	Photovoltaic system
	Wind turbine
EM – Energy-saving measures [14], [15], [16], [17], [18]	Use of test engineers during construction
	Coating of the tunnel ceiling with reflective materials
	Increasing the reflectance of the tunnel wall through wall panels
	Use of components with higher efficiency
	Retrofitting existing systems with LED-technology – the original luminaire positions are retained
	Re-equipping with LEDs vs. existing sodium vapor lamps – the luminaire positions are re-determined
	Counter-beam principle for entrance lighting
	Road surface with different luminance coefficients (q_0)
	Lightwell (saw-tooth roofs) in the viewing section (= section with the length of the stopping sight distance immediately behind the tunnel entrance)
	Wetness-dependent speed reduction
	Portal design
	Energy-saving potential through the use of frequency-controlled jet fans
AB – Aspects of operational management [19], [20], [21], [22]	Annual calibration of sensors
	Recording of energy data and benchmarks
	Demand-based control of the ventilation system during normal operation
	Regulation-compliant nighttime dimming of tunnel lighting
	Demand-based control of entrance lighting based on L_{20}

Each measure was evaluated for applicability, effectiveness and lifecycle cost impact. Measures at impact levels 1 to 3 typically reduce the expected annual energy consumption by a few percent. Measures at levels 4 and 5 achieve significantly higher savings – starting around 8-10 % and in individual cases even reaching up to 30 % of the total energy consumption. Some measures have a certain range of impact levels and a specific quantification depends on the respective project and must be determined individually.

A small selection of measures and their levels can be seen in **Figure 5** and illustrates the following measures:

- EQ1 – Generation of electrical energy from air currents
- EQ2 – Geothermal energy – absorber tubes
- EQ3 – Geothermal energy – combination of open system with absorber tubes
- EQ4 – Photovoltaic system
- EM1 – Use of test engineers during construction
- EM2 – Coating of the tunnel ceiling with reflective materials
- EM3 – Increasing the reflectance of the tunnel wall through wall panels
- EM4 – Use of components with higher efficiency
- EM5 – Retrofitting existing systems with LED-technology – the original luminaire positions are retained
- AB1 – Annual calibration of sensors
- AB2 – Recording of energy data and benchmarks
- AB3 – Demand-based control of the ventilation system during normal operation

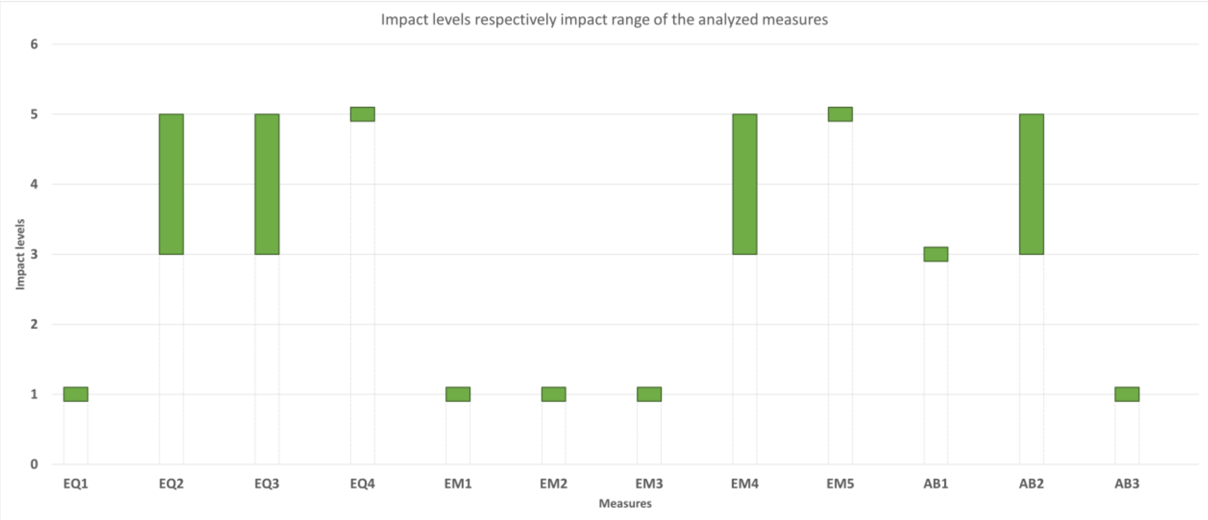

Figure 5: Excerpt from the range of impact levels of measures

In addition to quantitative effects, qualitative benefits such as improved visibility, safety and reliability are a by-product of some measures and were assessed. The catalogue is designed as a living tool, allowing future updates as new technologies and operational experiences emerge.

6. SUMMARY AND CONCLUSION

The presented results demonstrate that energy management and efficiency improvement in road tunnels is in many ways feasible. The analysis of the tunnels across the DACH region confirmed that lighting is the dominant energy consumer, emphasizing the relevance of optimized design, control and maintenance.

The developed energy management framework provides a practical methodology to:

- Identify and monitor energy flows and consumption patterns
- Integrate renewable energy sources directly into tunnel infrastructure
- Evaluate and prioritize efficiency measures based on technical and economic criteria
- Establish transparent performance indicators and benchmarks

Applying these principles can achieve measurable reductions in operational costs and CO_2 emissions while maintaining full safety and functionality. Furthermore, the proposed framework aligns with current European energy efficiency regulations and supports long-term sustainability goals in tunnel infrastructure management.

Future work should focus on expanding the availability and resolution of real energy demand data to further refine benchmarks. In combination with digital monitoring and predictive control systems, these developments will enable data-driven and adaptive tunnel operation, forming the foundation of future energy-efficient and resilient road infrastructure.

7. REFERENCES

[1] *Richtlinie (EU) 2023/1791 des Europäischen Parlaments und des Rates vom 13. September 2023 zur Energieeffizienz und zur Änderung der Verordnung (EU) 2023/955 (Neufassung) (Text von Bedeutung für den EWR), ABl. L 231 vom , pp. 1–111.*

[2] *Energieeffizienz-Reformgesetz 2023 – EEff-RefG 2023 (240/ME).*

[3] BMDV, *Bundesministerium für Digitales und Verkehr,* Berlin, 2024.

[4] Österreichische Forschungsgesellschaft Strasse, Schiene, Verkehr (FSV), *Richtlinien und Vorschriften (RVS) für den Straßenbau,* Wien.

[5] A. PEÑA-GARCÍA und D. GÓMEZ-LORENTE, Installation of solar panels in the surroundings of tunnel portals: A double-targeted strategy to decrease lighting requirements and consumption, Grenada: Tunnelling and Underground Space Technology, 2020.

[6] P. STURM, D. FRUHWIRT, R. SEEBACHER und K. KRISCHAN, „Tunnelkraftwerk - Möglichkeit von Stromerzeugung aus meteorologisch oder thermisch bedingten Luftströmungen in Straßentunneln," Graz University of Technology, Graz, 2023.

[7] OVE ARUP & PARTNERS LIMITED, „Geothermal use of tunnels," ohne Verlag, London, 2022.

[8] T. GEISLER, „Assessment of geothermal power in tunnels using open hydrothermal systems and engineering optimization option," Institute of Rock Mechanics and Tunnelling, Graz, 2024.

[9] T. GEISLER, G. KAML und T. MARCHER, „Sustainable energy from the depths: Optimization strategies for hydrothermal tunnel water systems," *Geomechanics and Tunnelling,* Bd. 17, Nr. 5, pp. 426-436, 1 Oktober 2024.

[10] C. MOORMANN, G. MARZAHN, I. KAUNDINYA und M. POZYBILL, „Nachhaltigkeit im Tief- und Tunnelbau durch innovative geothermische Konzepte," ohne Verlag, Stuttgart, 2022.

[11] R. BORRMANN, K. REHFELDT und D. KRUSE, „Volllaststunden von Windenergieanlagen an Land - Entwicklung, Einflüsse, Auswirkungen,“ Deutsche WindGuard GmbH, Varel, 2020.

[12] S. LÜERS und A.-K. WALLASCH, „Vorbereitung und Begleitung bei der Erstellung eines Erfahrungsberichtes gemäß § 97 Erneuerbare-Energien-Gesetz (EEG 2017) zum spartenspezifischen Vorhaben Windenergie an Land - Kostensituation der Windenergie an Land Stand 2023,“ Deutsche WindGuard, Varel, 2023.

[13] T. HOCHSTEIN, E. SCHRECK, C. MOORMANN und T. KUGLER, „Geothermal use of groundwater in tunnels combined with direct passive road surface temperature control,“ *Geomechanics and Tunnelling,* Bd. 17, Nr. 5, pp. 437-444, 1 Oktober 2024.

[14] crypta.sec conceptum GmbH, „B171 Tiroler Straße, Stadtbergtunnel Rattenberg, Beleuchtungsmessungen,“ Amt der Tiroler Landesregierung, 2022.

[15] S. KRISPEL, M. PEYERL und G. MAIER, „Erhöhung der Sicherheit und Energieeinsparung in Tunnelbauwerken durch Optimierung der Materialauswahl von Fahrbahndecken,“ pp. 499-508, 31 Mai 2019.

[16] C. YANG und S. FAN, „Energy-Saving Performance Studies of Road Tunnel Luminaries,“ *Applied Mechanics And Materials,* Bd. 291 bis 294, pp. 654-660, 2013.

[17] F. SALATA, I. GOLASI, A. POLIZIANIA, A. FUTIA, E. VOLLARO, M. COPPI und A. VOLLARO, „Management Optimization of the Luminous Flux Regulation of a Lighting System in Road Tunnels. A First Approach to the Exertion of Predictive Control Systems,“ *Sustainability,* Bd. 8, Nr. 11, p. 1092, 25 Oktober 2016.

[18] L. MORETTI, G. CANTISANI, L. CARRARINI, F. BEZZI, V. CHERUBINI und S. NICOTRA, „Italian Road Tunnels: Economic and Environmental Effects of an On-Going Project to Reduce Lighting Consumption,“ *Sustainability,* Bd. 11, Nr. 17, p. 4631, 26 August 2019.

[19] M. PEHNT, M. ARENS, M. DUSCHA und W. EICHHAMMER, „Energieeffizienz: Potenziale, volkswirtschaftliche Effekte und innovative Handlungs- und Förderfelder für die Nationale Klimaschutzinitiative. Endbericht,“ Institut für Energie- und Umweltforschung (ifeu), Heidelberg, 2011.

[20] A.-C. AGRICOLA, J. PERNER, S. JOEST, D. BOTHE, M. CZERNIE, R. HEUKE, D. KALINOWSKA und S. PETERS, „Steigerung der Energieeffizienz mit Hilfe von Energieeffizienz-Verpflichtungssystemen,“ Deuschte Energie-Agentur & Frontier Economics, Berlin, 2013.

[21] T. FLEITER, B. SCHLOMANN und W. EICHHAMMER, Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien - Einsparpotenziale, Hemmnisse und Instrumente (ISI-Schriftenreihe "Innovationspotenziale"), Stuttgart: Fraunhofer-Verlag, 2013.

[22] Autonome Provinz Bozen - Südtirol, „Autonome Provinz Bozen - Südtirol,“ 2013. [Online]. Available: https://news.provinz.bz.it/de/news-archive/432391. [Zugriff am 20 Oktober 2025].