SUSTAINABLE TUNNEL OPERATION GENERATION OF ELECTRICITY THROUGH THERMAL AND PRESSURE-DRIVEN AIRFLOWS

[1]Peter Sturm, [2]Dietmar Harbauer, [3]Roland Seebacher, [1]Daniel Fruhwirt, [3]Klaus Krischan
[1]Graz University of Technology,
Institute of Thermodynamics and Sustainable Propulsion Systems, AT
[2]ASFINAG, AT
[3]Graz University of Technology, Institute of Electric Devices and Machines, AT

DOI 10.3217/978-3-85125-996-4-06 (CC BY-NC 4.0)

ABSTRACT

The energy demand for the operation of a road tunnel is considerable. This results on one hand in high operation costs and – as the production of electricity is not free of fossil fuels – in a significant CO_2 footprint. There is an evident need to reduce energy costs as well as to improve the CO_2 footprint. Due to the high energy costs, alternative options for generating electricity are being considered. The question arises as to whether mechanical ventilation systems can be used in reverse operation to generate electricity in road tunnels when pressure-driven air flows are present.

This paper deals with aspects of pressure-driven air flows in general and their use for generating electricity in electrical machines. As a first step, an analysis was carried out for standard 2-lane tunnels with different lengths and meteorological pressure differences. As a second step, recorded pressure differences between portals or shafts were evaluated for selected Austrian road tunnels.

The calculation of the annual energy quantities for possible electricity generation was based on the actual pressure differences in tunnel systems in the Austrian motorway and expressway network. Based on the available measurement data, those tunnel systems that have a high meteorologically related pressure difference were selected for further consideration. Taking into account the aerodynamic conditions and the expected efficiencies of electricity generation, an expected annual amount of energy can be estimated.

Keywords: sustainable tunnel operation, meteorological pressure differences, electricity generation

1. INTRODUCTION

The operation of road tunnels is energy intense. According to information provided by ASFINAG, the Austrian motorway operator [1], a total of 108 GWh of electricity was consumed in Austria's motorway tunnels in 2018. This corresponds to 76% of the total electricity consumption of the Austrian motorway network. ASFINAG's strategic goals for 2030 are to reduce the energy consumption by 20%, cover their own electricity needs independently and increase the production of renewable energies to 100 MWp [1].

Within the framework of the tunnel power plant research project (Future Mobility Funding Program MdZ-VIT, FFG Project 893655), the possibility of generating electricity from meteorologically or thermally induced air flows in road tunnels was to be investigated [2].

Air flows in tunnel systems occur due to pressure differences between the portals. These pressure differences have meteorological causes. To a certain extent, the temperature differences between the air outside and inside the tunnel also contribute to the development of an air flow. Flows generated by the momentum of moving vehicles in the tunnel are not considered further because they are generated by the vehicle itself. Any "use" of this factor would therefore only be a transfer from one energy source (vehicle propulsion system) to another (electricity generation).

In high vertical shafts, such as those found in transverse-ventilated tunnel systems, thermally induced buoyancy flows occur, which can also be superimposed by different barometric pressures.

2. THEORETICAL POTENTIAL FOR ELECTRICITY PRODUCTION FROM AIR FLOWS IN TUNNELS

2.1. Mathematical model

Basically, air flows at higher speeds are turbulent flows. Such flows are usually three-dimensional. In the case of tunnels, however, a one-dimensional channel flow can be assumed due to the very long length of the tunnel. The extended form of Bernoulli's equation is applicable to such flows. Bernoulli's equation is valid for an incompressible, frictionless flow or, more precisely, along a streamline. In order to take friction and other resistances into account, it is extended so that these losses are taken into account by means of characteristic numbers with a quadratic dependence on the flow velocity. For a channel/tunnel with a constant cross section, the extended form of Bernoulli's equation is as follows:

$$\Delta p_{tot} = (\zeta_E + 1) * \frac{\rho}{2} * u_V{}^2 + \lambda * \frac{l}{D} * \frac{\rho}{2} * u_V{}^2 + \Delta p_F + \Delta p_T + \Delta p_{Turb}$$

The individual parameters of the equation are:

Δp_{tot}: pressure difference between portals, adjusted according to height

ζ_E: entrance loss for portal, the value 1 within the brackets represents the loss of kinetic energy at the exit

ρ: air density

u_V: air velocity in the tunnel or shaft

λ: wall friction coefficient

l: length of the tunnel or shaft

D: hydraulic diameter

Δp_F: pressure change due to vehicles in the tunnel (can be positive or negative)

Δp_T: thermally induced buoyancy forces in case of inclinations

Δp_{Turb}: pressure loss due to a turbine in generator mode

Thermally induced pressure differences can occur due to the different temperatures between the portal and the inside of the tunnel. They can be approximated as follows:

$$\Delta p_T = \Delta H * \rho * g * \frac{T_V - T_0}{T_V}$$

Where ΔH is the height difference between the portals, ρ is the air density outside the tunnel, g is the acceleration due to gravity, T_V is the mean temperature in the traffic area and T_0 is the absolute temperature of the outside air at the portal of the air inflow.

While thermally induced pressure differences in tunnels are of little relevance for the considerations made here due to the usually relatively small longitudinal gradient, this is very significant for high vertical shafts. Here, the temperature differences between the shaft base and shaft head act as driving forces. If one disregards a possible heat flow via the shaft walls between the surrounding rock and the flowing air, one can assume an almost isothermal behaviour of the air column. The equation shown above remains the same in principle. The driving force is now the difference between the temperature inside (= shaft base) and outside (= surroundings of the shaft head). Further influencing variables, such as wall friction, are small in comparison.

2.2. Theoretically achievable turbine power

The technical work or power of a turbo machine can be calculated as follows, disregarding the effects of friction and changes in external energies (kinetic, potential energy, etc.) and assuming a constant density in accordance with the first law of thermodynamics:

$$P_{Turb} = \dot{m} * \int_1^2 v\, dp = \dot{V} * \int_1^2 dp = A * u_V * (p_2 - p_1) = -A * u_V * \Delta p_{Turb}$$

The volume flow is calculated by multiplying the tunnel cross section (A) by the average air velocity in the tunnel (u_V). Since the pressure difference in the tunnel utilised by the turbine is quadratic to the air velocity, this results in a cubic dependence of the power on the air velocity.

A maximum value analysis can be used to determine the optimum air velocity at which (theoretically) the maximum power yield is achieved[1].

$$P_{Turb\_opt} = A.\frac{2}{3}.\sqrt{\frac{1}{3}.\frac{\Delta p^3{}_{tot}}{k_{Tunnel}}}$$

Whereby k_{Tunnel} represents the resistance of the tunnel multiplied by $\frac{\rho}{2}$.

Applying the above-mentioned equation to a standard two-lane tunnel with a cross section of 55 m^2 and assuming typical values for air density (1.175 kg/m^3), entrance loss (0.85), wall friction (0.016) and efficiency of the turbine (0.7), the theoretically achievable turbine power output can be calculated as a function of pressure difference between the portals and tunnel length.

[1] Thermally and vehicle induced forces neglected

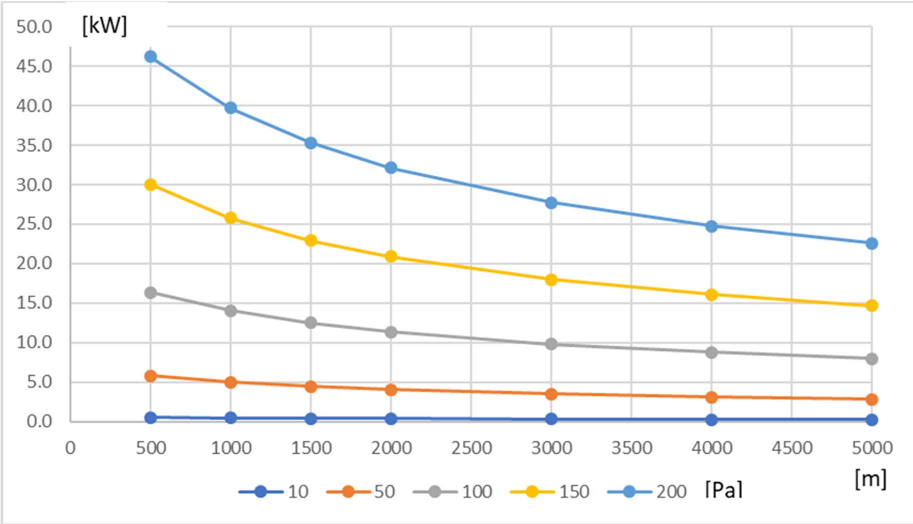

Figure 1: Theoretically achievable turbine power as a function of pressure difference between portals and tunnel length

As shown in Figure 1, a higher turbine power can only be achieved by combining a high pressure difference and a short tunnel length. This is of course diametrically opposed to the real conditions, as the pressure differences between the portals are usually rather small in short tunnels.

3. POSSIBLE APPLICATION TO AUSTRIA'S TUNNELS

Due to Austria's geographical location in the middle of Europe and its mountainous terrain, there are a very large number of road tunnels. According to [3], some 170 tunnels with a total length of around 400 km are currently in operation in the expressway and motorway network alone. As the Alps transect Austria in a west-east direction and act as a weather divide, quite considerable pressure differences can be expected. Since many tunnels are also equipped with a mechanical ventilation system, it can generally be assumed that many of them might be suited to the energetic use of air flows to generate electricity.

3.1. Pressure differences at selected Austrian tunnels

As part of tunnel construction and renovation projects, ASFINAG repeatedly carries out meteorological measurements on tunnel sections within the motorway network. These measurements usually extend over a period of one year (365 days) and concern the usual meteorological parameters such as absolute pressure, wind speed and wind direction distribution as well as air temperature.

In principle, a distinction is made between the two parameters "barometric air pressure" (static pressure) and "wind pressure" (dynamic pressure). Wind speeds (or the dynamic pressure) can in principle be measured with a higher accuracy than the absolute pressure (static pressure) or the resulting pressure difference between the two portals. It should be noted that, depending on the local location of the monitoring sensors and on the measuring conditions, both parameters may be linked. For example, if tunnel portals are located together in the same climatological area (e.g. in the same valley or in basins), a barometric pressure difference automatically acts as wind. Adding these two components would automatically lead to a double assessment in such a case. Simultaneous consideration of both pressures therefore only makes sense if there are decoupled meteorological situations at the two portals, as is the case, for example, with tunnels in the area of major Alpine crossings (usually combined with high overburdens).

As the two portals of tunnels without additional entrances or exits are usually at different altitudes, the measured data of the respective absolute pressure must be corrected in relation to the altitude of the monitoring sensor in accordance with ISO standard atmosphere (ISO 2533).

In a preselection process, data from 18 road tunnels (17 twin tube tunnels, one tunnel with bidirectional traffic) with a length of 1.5 to 14.0 km was selected. These tunnels included longitudinal ventilation systems as well as transverse ventilation systems. The shaft heights of the transverse ventilated tunnels ranged from 80 m to 780 m. Detailed data from all the investigated tunnels as well as details concerning the data processing can be found in reference [4].

In the majority of the road tunnels listed in Figure 2, the portal pressure difference is already below 50 Pa in the 95% percentile. For further exemplary considerations, therefore, only the Kalcherkogel and Semmering tunnels – representative of longitudinally ventilated tunnels – and the long Alpine crossing transverse ventilated tunnels are considered.

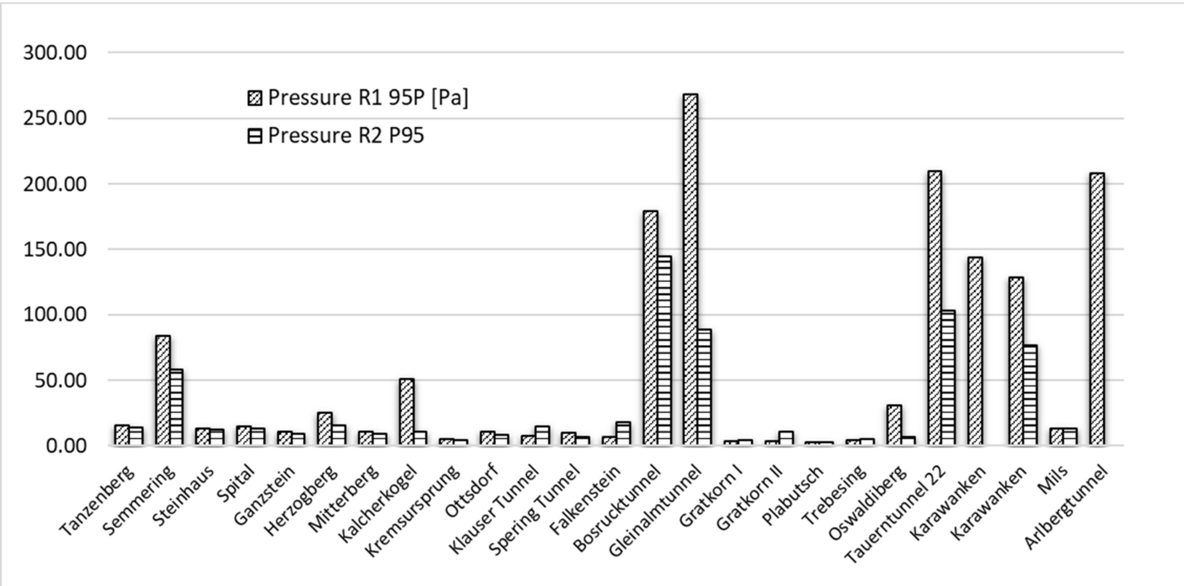

Figure 2: Meteorologically caused pressure difference between portals, 95% percentile values, R1 and R2 denote the different tunnel tubes

Table 1: Meteorologically caused pressure difference between portals

Name	Length [m]	5-P [Pa]	50-P [Pa]	95-P [Pa]	98-P [Pa]
Kalcherkogeltunnel*	2150	1	14	65	78
Semmering*	3062	3	36	99	131
Karawankentunnel**	7864	4	49	144	177
Bosrucktunnel**	5500	8	73	197	232
Arlbergtunnel**	13972	7	66	208	254
Gleinalmtunnel**	8320	7	77	258	308

* Longitudinal ventilation, ** Transverse ventilation

As can be seen on Table 1, the median pressure difference in the selected longitudinally ventilated tunnels is already noticeably below 50 Pa and between 50 and 77 Pa in the long transalpine tunnels. This already considerably limits the possibilities for utilising pressurised air flows to generate electricity. Table 2 shows the values for selected vertical shafts.

Table 2: Buoyancy caused pressure in vertical shafts

Name	Height [m]	5-P [Pa]	50-P [Pa]	95-P [Pa]	98-P [Pa]
Gleinalm North	366	-30	44	204	299
Arlberg Albona	778	24	148	370	473
Plabutsch North	240	28	101	205	232

3.2. Electromechanical requirements for power generation

Before deploying new electromechanical equipment in the tunnel, the utilisation of the existing ventilation system in reverse mode as a turbine/generator unit shall be considered. The fan of a ventilation system is usually driven by an induction (asynchronous) motor.

General considerations

In order to bring an induction machine into generator operation, the rotating field must rotate slightly slower than the rotor. If the machine is supplied from the mains at a constant frequency, the synchronous speed (zero torque) is determined by the mains frequency and the number of pole pairs of the machine. The turbo machine must therefore change its behaviour at an almost constant speed in order to switch from fan operation to turbine operation. This would at least be conceivable with fans with adjustable blades. In case of a pole changing induction motor, the synchronous speed can be varied in fixed ratios by pole changing.

The rotor speed of synchronous machines is determined by the supply frequency and the number of pole pairs of the machine. Again, a transition from motor to generator operation with a constant frequency supply has to be caused by the load.

The directly grid connected induction machine allows the operation of the machine as a motor as well as a generator. The electrical machine (EM) drives a fan (F) or is driven by a turbine (T) (see Figure 3).

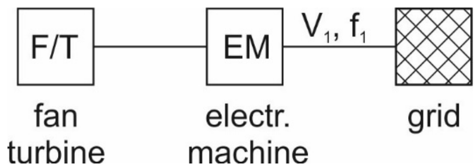

Figure 3: Induction machine directly connected to A/C grid of a certain voltage V_1 and a frequency f_1

If the fan requires a distinct change of speed to operate in regenerative mode, an adjustable speed drive is required. For AC machines this speed variation is achieved by adjusting the amplitude and frequency of the supply voltage. This applies to both the induction and the synchronous design of the AC machine. A DC inverter would be suitable to fulfil this task.

Currently the majority of existing speed-controlled jet fans in Austria are equipped with non-regenerative DC-link inverters, supplied by the grid via an uncontrolled rectifier. In order to supply electrical energy back into the grid, a grid side inverter is required (see Figure 4).

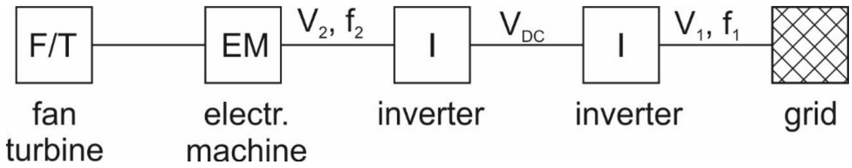

Figure 4: Adjustable speed drive, consisting of AC machine, machine side inverter, DC-link (V_{DC}) and grid side inverter

Existing equipment

The electromechanical equipment in the selected tunnels has the following characteristics:

- Jet fans: induction machines either with direct connection to the mains at 400 V/50 Hz or inverter driven (non-generative) at 400 V/50 Hz or 690 V/50 Hz
- Axial fans in transverse ventilated tunnels: pole-changing induction machines with direct connection to the mains, either 6 kV/50 Hz or 690 V/50 Hz, pitch-controlled. One tunnel is equipped with pitch and inverter-controlled fans, but the inverter is non-regenerative.
- All machines are designed for continuous operation.

4. ESTIMATION OF ANNUAL ENERGY QUANTITIES FROM THE PRESSURE DIFFERENCES

In order to estimate the potential power available for electricity generation, it is necessary to know the pressure differences and the air flow rate through the tunnel. In addition, tunnel-specific data is required in order to establish the tunnel resistance. The following boundary conditions were assumed:

- Cross section and number of jet fans or turbines as in the current situation
- Cross section of air ducts in transverse ventilated tunnels does not change and can be used over the full length of the tunnel
- No changes in tunnel geometry

Table 3: Relevant parameters for the geometry of the considered road tunnels

	Semmer-ing	Kalcher-kogel	Arlberg-tunnel	Bosruck	Gleinalm	Karawan-ken
Cross section jet fan/turbine [m²]	1.23	2	2	2	2	2
Cross section air duct [m²]			11.5	12.77	13.69	9
Number of jet fans	14	10	3	10	14	10
Tunnel length [m]	3,062	2,150	13,972	5,500	8,320	7,864

For the consideration of buoyancy driven air flows in the vertical shafts of transverse ventilated road tunnels, the following geometry was used:

Table 4: Relevant parameters for the geometry of the considered tunnel shafts

Tunnel shaft	Gleinalm North	Gleinalm South	Arlberg Albona	Arlberg Maienwasen	Plabutsch North	Plabutsch South
Cross section fresh-air duct [m²]	17.3	17.3	20	23.5	28	28
Cross section return-air duct [m²]	13.7	13.7	24.5	28.79	28	28

Hydraulic diameter fresh/return-air [m]	4.2/3.6	4.2/3.6	4.3/4.5	4.5/5.2	je 5.14	je 5.14
Shaft height [m]	366	287	778	260	240	90

For the purpose of comparability, the following assumptions were made for the other necessary input data:

- Available tunnel cross section 48.7 m², hydraulic diameter 6.9 m, air density 1.1 kg/m³, wall friction coefficient 0.016, pressure loss entrance 0.3 (tunnel portal and horizontal air ducts) or 1 (vertical shaft).
- When considering the air flow passing a wind turbine in a road tunnel, it has to be considered that due to the increased air resistance inside the turbine, a considerable amount of air will "bypass" the turbine. According to Betz [5] and [6], a wind turbine is capable of utilising some 60% of the theoretical available energy of a free-flowing wind. This is different to the situation in an air duct, where the full cross section can be utilised for electricity generation.
- Turbine efficiency (isentropic): 0.7
- Efficiency of electrical machines:
  - For those tunnels for which machine data was available, a constant loss according to rated power was assumed.
  - A similar procedure is used for the remaining tunnels, but simplified data values from machines of a similar size were used.
  - The energy losses from the inverters were calculated according to IEC 61800-9-2:2017 for the rated operation point of the electrical machines.
  - A transfer of power into the grid can only happen when the usable power is higher than the power loss by the electrical machine and inverter (for details see [4])

The pessimistic treatment of the electrical losses, in particular, resulted in a "loss" of the power share in the low Watt range. As these power ranges most frequently during a year, the total loss in usable electrical energy is quite considerable. As shown in Figure 5, there is a big difference between the work provided by the turbine (dashed line) and the equivalent delivered into the electrical mains (solid line). But this figure also shows the fact that the required power range of the turbo machine is in the range of a few W to 1.5 kW in the case of the jet fan application, while for the operation in a shaft, the power range is between a few W and 30 kW. Compared to the operation range in fan mode, in both cases this is one to two orders of magnitude higher. This suggests that a simple usage of existing electrical drives for both modes of operation does not seem to be feasible.

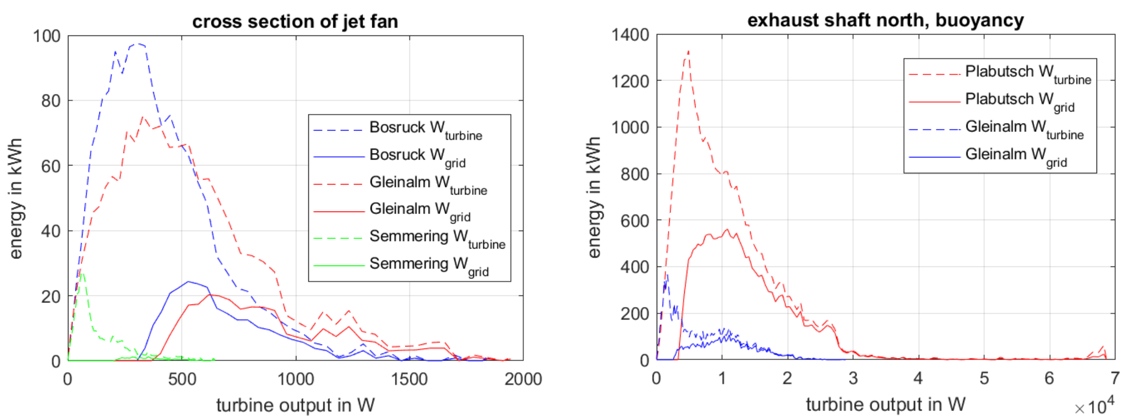

Figure 5: Comparison between work provided by the turbine (dashed lines) and delivered into the electrical grid (solid line) for jet fan application (left) and shaft application (right)

Other influencing variables such as variable flow speed, inertia of the air mass etc. were not taken into account when determining the annual energy quantities. Further details about input and boundary conditions can be found in reference [2] and [4].

4.1. Utilisation of portal-to-portal pressure differences (longitudinal airflow)

In twin-tube tunnels with bidirectional traffic as well as when utilising the horizontal airducts in transverse ventilated tunnels, active operation of the ventilation system during normal operation happens very rarely in the considered road tunnels. Hence the periods with an active longitudinal ventilation system were neglected in the estimation of the yearly achievable electrical energy.

On the basis of the available pressure gradient, the following values for the amount of electrical energy that can be generated annually can be estimated, taking into account the above-mentioned efficiencies and boundary conditions (see Table 2.

As expected, higher meteorologically induced pressure differences only occur in longer road tunnels (with a higher overburden), but these also have a higher pressure loss due to their greater length; these two factors – high barometric pressure differences and long tunnel length – are diametrically opposed. As a result, the power generation potential in the purely longitudinally ventilated tunnels is low, as expected.

Table 5: Generated electrical energy on an annual basis [kWh]

	Per jet fan*	All jet fans*	Utilization of air duct
Kalcherkogel	15.6	156	-
Semmering	10.8	151	-
Arlberg	103.8	313	1943
Bosruck	206.4	2064	5323
Gleinalm	231	3234	5079
Karawanken	85.2	1191	1645

* Generator mode (turbine)

4.2. Utilisation of buoyancy driven air flows in vertical shafts

Transversely ventilated tunnels with a high air intake and exhaust shafts generally have greater potential for utilising buoyancy driven air flows to generate electricity. However, these shafts are also used more or less often during normal operation to ensure the necessary air quality in the tunnel. This is very often the case with a single-tube tunnel such as the Arlberg Tunnel. In twin-tube tunnels - such as the Gleinalm Tunnel - self-ventilation by vehicles is often sufficient so that the shaft fans only rarely need to be used. Such aspects must of course be considered when estimating the potential for electricity generation. This aspect means that the high pressure differences acting in the Arlberg tunnel can only be utilised for about 1/3 of the year, while in the other long double-tube tunnels they can be utilised almost 100% of the time.

Table 6: Generated electrical energy in vertical shafts on annual basis [kWh]

Tunnel shaft	Gleinalm North	Gleinalm South	Arlberg Albona	Arlberg Maienwasen	Plabutsch North	Plabutsch South
Electrical Energy [kWh]	5,545	2,628	19,272	4,380	24,538	5,056

When discussing the values provided in Table 6, it has to be considered that the high availability of the Plabutsch north shaft, combined with a very high volume flow (big cross section), results in the highest achievable amount of generated electrical energy. On the other side, the low availability of the Albona shaft (which is by far the highest vertical shaft of a road tunnel in Europe) strongly reduces the possibility of electricity generation in this shaft.

5. SUMMARY AND CONCLUSION

The effort to reduce the high energy consumption (and CO_2 footprint) of Austria's road tunnels and to achieve cost reductions leads to the investigation of innovative concepts for electricity generation. In one of these concepts, the question arose as to whether mechanical ventilation systems can be used in reverse operation to generate electricity in road tunnels when pressure-driven air flows are present.

The power of a turbo machine is proportional to the volume flow rate through this machine and the pressure drop across the machine. This means that in a duct flow there is a cubic relationship between air speed and machine power. It can also be expressed as a relationship between machine power and the acting pressure difference to the power of 3/2 and a proportional factor dependent on the tunnel resistance. From this relationship, it can be deduced that the higher the pressure differences between the portals or across shafts and the shorter the tunnel/duct, the higher the electrical power that can be generated.

This contradicts reality, as high meteorologically caused pressure differences only occur in tunnels that cross under a large mountain range. With thermally driven flows, shafts with appropriate heights are required in order to be able to convert a relevant amount of energy.

The use of existing fans in generator operation is contradicted by the fact that the power requirement in fan operation is orders of magnitude higher than in generator operation. The currently installed electrical machine part is therefore unsuitable for economical generator operation due to the high inherent losses.

The calculation of the annual amounts of energy that can be utilised to generate electricity was based on the actual pressure differences in tunnel systems in the Austrian motorway and expressway network. Based on this data, the tunnel systems with high meteorologically-generated pressure differences were selected for further consideration. For the respective tunnels, it was assumed that the existing ventilation equipment shall be used in reverse mode for electricity generation.

When considering the longitudinal ventilated tunnels, the reverse operation of the turbo machines would lead to an electricity production in the range of 160 kWh. Using the turbo machines in the existing transverse ventilated tunnels results in an electricity production in the range of between 1,620 kWh to 3,230 kWh. As the transverse ventilated tunnels offer the possibility to use the air duct (above the false ceiling), an annual electricity production in the range between 1,645 kWh and 5,320 kWh would be achievable.

When utilising the big vertical shafts of transverse ventilated road tunnels, the availability of such a shaft is of high importance. In single-tube tunnels with bidirectional traffic, the ventilation is quite often used during normal operation. This is totally different for Austria's double-tube tunnels with unidirectional traffic. In those tunnels additional mechanical ventilation during normal operation is in most cases not needed. The latter is the case e.g. when considering the Plabutschtunnel north shaft. Here an annual electricity production up to 24,540 kWh would be achievable.

In order to be able to classify the values listed above correctly, they can be compared with the average annual electricity consumption of an Austrian two-person household. This amounted in 2022 to almost 3,100 kWh.

However, for all the investigated cases, it must be mentioned that the numbers given above are rough estimations and can vary in both directions. The following restrictions need to be mentioned:

- Simplifying assumptions were made regarding efficiencies in the power generation chain (from the turbine to the power grid interface). Values were assumed that must at least be achieved in accordance with normative specifications. Lower losses are to be expected in real electrical systems, which means that a higher annual output per system can be expected.
- The benchmark refers to a theoretical machine choice. When installing small wind turbines specifically tailored to the existing performance potential, a higher yield may be achieved.
- The results relate to optimised, low-resistance flow conditions in air ducts and shafts. For example, inflow losses via any air damper, deflections in the air path etc. were not taken into account in the estimates. Such considerations would require detailed project planning.

Generally speaking, it can be concluded that a simple upgrading of existing engine and turbo machine combinations (ventilation systems) by means of additional electrical equipment such as inverters will not be sufficient to end up with an economically feasible electricity production system. The installation of additional wind turbines, in combination with all the required civil works for improving the air path, would be required. Whether such an effort is economically and also ecologically feasible has to be decided on a project-by-project basis. However, the investigations showed that at best, high buoyancy driven air flows in high vertical shafts could be used to generate electricity to a feasible extent, provided they are not occupied by ventilation for normal operations.

6. REFERENCES

[1] List R.: The way to sustainable and efficient road tunnel operation, International PIARC Seminar on "Advances in Design, Construction and Operation of Tunnels, Dehradun, India, April 19th 2023

[2] FFG MdZ: https://projekte.ffg.at/projekt/4429532, access Dez. 28th 2023

[3] BMK: Statistik Straße und Verkehr, Federal Ministry, Republic of Austria, Climate Action, Environment, Energy, Mobility, Innovation and Technology, Bundesministerium für Klimaschutz, Umwelt, Energie; Vienna, June 2023

[4] Sturm P., Fruhwirt D., Seebacher R., Krischan K.: Möglichkeit von Stromerzeugung aus meteorologisch oder thermisch bedingten Luftströmungen in Straßentunneln, ITnA Bericht Nr. I-30/23/PSt/V&U Inst_21/014/1640, https://doi.org/10.3217/0aa6q-c0k47, Graz University of Technology

[5] Betz, A.: Das Maximum der theoretisch möglichen Ausnützung des Windes durch Windmotoren. *Zeitschrift für das gesamte Turbinenwesen*, Band Heft 26, 1920

[6] Schaffarcyk, A.P.: Introduction to Wind Turbine Aerodynamics, Springer Verlag Berlin, 2014