Supporting the implementation by NRAs of renewable energy technologies in the road infrastructure

Deliverable 2.1

Report of main renewable energy technologies (RETs) for the road infrastructure

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1 INTRODUCTION

The information presented in this document responds to the development of Task 2.1 of the project, with title: “Identification and first screening of renewable energy technologies with the highest potential for their application on the main topologies of NRA’s assets”. The renewable energy technologies (RETs) that are more suitable for installation along the road asset have been described along with the most relevant topologies for their implementation. For this, an extensive state-of-the-art review has been carried out, for which several different sources of information have been used: technical literature (research papers, review papers, congress proceedings, etc.), institutional respositories, magazines, newspapers, technical brochures or technical data from RET manufacturers, among others. Then, previous experiences by the National Road Administrations (NRAs) on the use of renewable energy technologies worlwide have been outlined in order to provide further information regarding their energy performance, maintenance needs, security events or safety issues. In total, more than 150 references have been used for the development of these main sections, not to forget the consultation with several experts on the topic.

As very scarce information is available regarding some of these installations, a questionnaire was designed and delivered to representatives of 16 European countries in order to collect further reliable information. Results obtained from the survey are here referred along with the information provided by other external experts consulted by email. Finally, a first screening of renewable energy technologies and road topologies has been performed mainly based on the Technology Readiness Level (TRL) and Market Readiness Level (MRL) but also on other important criteria.

With the information provided by this Deliverable, a deeper analysis of the distributed renewable energy resources and their optimal integration with the existing power systems and road infrastructures will be carried out in Deliverable 2.2 as well as an overview of current knowledge on the environmental impact of the energy generation technologies.

2 ROADSIDE RETS SUITABLE FOR NRAS

In this chapter the renewable energy technologies (RETs) more suitable for implementation by NRAs along the road asset have been described: wind energy, solar PV energy, small-scale hydro power and micro-scale biomass power plants. The different technologies involved, elements, materials, design parameters as well as cleaning and maintenance tips are here defined. For all of them, the area available is a relevant factor to be taken into account at the moment to opt for one or another, because it is directly related to the power extracted.

2.1 WIND ENERGY

A wind turbine, or wind energy converter, transforms the kinetic energy of the wind in electric power, passing by the intermediate step of conversion to mechanical energy or rotating mechanical energy through the blades. Wind turbines may be classified as lift, resistance and/or hybrid depending on what forces generated by the wind are used as driving force. Traditionally, wind turbines are classified into two big groups in relation to the position of their rotor respect to the ground plane:

- Vertical Axis Wind Turbine (VAWT).
- Horizontal Axis Wind Turbine (HAWT).

Another interesting classification for this study is the one according to the generation power, where two groups appear:

- Large-scale wind (0.8 - 15 MW).
- Small-scale wind (up to 50 kW).

However, the latter classification is not that simple to establish, as the range of power capacity will change depending on the country or rating institution considered. According to the International Electrotechnical Commission (IEC) the limit to differentiate small and medium size wind turbines is in the 50 kW. For other organizations like the American Wind Energy Association (AWEA), the Environmental and Energy Study Institute (EESI), the german Bundesverband WindEnergie (BWE) and RenewableUK, this limit is in the 200 kW, 100 kW, 75 kW and 100 kW (small to medium turbines), respectively. There is not fixed limit. On the other hand, the frontier between the medium and the large wind turbines (0.8-1 MW) seems to be more internationally defined.

In general, the energy efficiency of horizontal axis turbines is higher than that of the vertical axis turbines for wind power extraction and therefore, most wind turbines today are horizontal axis turbines (HAWT). On the other hand, VAWTs have recently experienced a significant development, having them advantages over the horizontal turbines such as an easier maintenance, a lower visual impact or lower noise pollution. In addition, the way the wind is affected by the obstacles (buildings) in an urban environment, makes the always smaller vertical axis turbines a more than suitable option for those urban conditions.

The main references used for the development of section 2.1 are: ABB (2012), Air Technology (2019), Al-Addous et al. (2020), Al-Aqel et al. (2016), Araujo et al. (2021), Atici et al. (2015), Barrett et al. (2014), Bina et al. (2018), Choi et al. (2013), Contreras and Mateo (2008), Ebrahimpour et al. (2020), Echevarría et al. (2008), EPAW (2017), Green Angel (2018), Hahn (2007), Hanssen et al. (2018), Hau (2006), IEC (2013), Jackson (2013), Klæboe and Sundfør (2016), Lechter (2017), Michaud et al. (2016), Namowitz (2015); Nordic Folkecenter (2016), Nordex (2017), Nordmann (2014), Patriksen et al. (2013), Paulides et al. (2009), Pernía and Hernández (2014), Ragheb (2019), Rediske et al. (2021), Schwnaz et al. (2014), Siyal et al. (2015), Sørensen et al. (2012), Wild horse (2012), Wind Models (2021), Windpowerengineering (2021) and Yáñez (2018).

2.1.1 LARGE-SCALE WIND ENERGY

Large wind will be considered for powers comprised between 0.8 and 15 MW being the main wind turbine configurations and their possible locations those described next.

2.1.1.1 Horizontal axis turbines

This type of turbine represents approximately 99% of the total large turbines. Among the horizontal axis turbines approximately 99% are of three blades versus the 1% of those of two. The horizontal axis turbine is the most extended model in front of those of two blades and a blade with counterweight. Most of the current three-bladed turbines have power capacities between 0.8 and 5MW, although there are off-shore wind turbine projects in the development phase that reach power ratings of 12-15 MW (Figure 1).

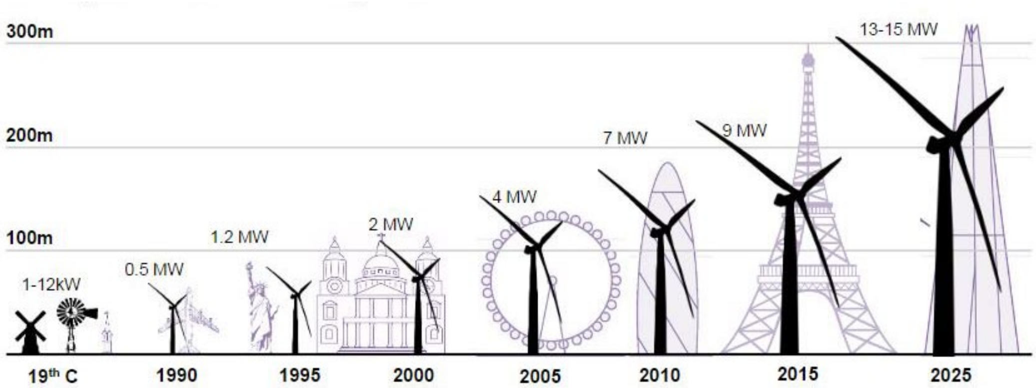


Figure 1.- Evolution of large three-bladed horizontal-axis turbines. Source: Bloomberg New Energy Finance

The increase of size in large three-bladed horizontal-axis wind turbines has the objective to maximise the energy captured by them. This is accomplished by:

- Increasing the rotor diameter in order to increase the area swept by the blades. By doubling the rotor diameter, the power capacity of the wind turbine increases fourfold.
- Increasing the height of the wind turbine in order to take advantage of the higher wind speeds. The power capacity of the wind turbines increases with the cube of the wind speed. In addition,

turbulence caused by the ground roughness decreases with height, which considerably reduces blade vibrations.

This tendency in the last decades has been possible mainly due to: new materials, the development of the power electronics and the more accurate and powerful CFD (Computational Fluid Dynamics) techniques.

In Figure 2 the different typical horizontal axis wind turbines are presented: one-bladed, two-bladed and three-bladed. Following, the main elements that conform a horizontal axis turbine are briefly defined.

Figure 2.- Horizontal axis turbines: one-, two- and three-bladed.

2.1.1.2 Main components of the large wind

In this section, the main components of the large scale horizontal axis turbines are defined: tower, blades, hub, multiplier, braking system, orientation systems, transformer, generator, converter and protections.

Tower

The first turbines used lattice towers. Today, tube towers are employed instead. Main aim of the tower is the support of the nacelle, which is the principal element of the turbine. Until recently, steel was the only material for the construction of the tower but as the height of the turbines increases, the concrete is more and more used for different reasons such as durability or easy construction.

Blades

The blades are the components that interact with the wind, so that they are designed with a profile that maximises their aerodynamic efficiency. The transverse section of the blade is big enough to achieve the necessary stiffness to stand the variable mechanical loads that appear in the normal functioning and that contribute to its damage. The blades are fabricated with light materials, such as fiber reinforced plastic, with good properties of resistance to wear. In blades of medium and small size turbines usually glass fiber or aluminium are used, while in the biggest blades carbon fiber is employed for those parts subjected to the most critical loads.

Hub

It is the component that connects the blades to the main axis, transmitting the power extracted from the wind and includes the mechanisms of power regulation. The hub is usually made of steel or cast and is protected externally with an oval cover. Depending on the degree of freedom that the hub lets the blades three three types of hub can be distinguished: rigid, teetering and hinged.

Multiplier

Normally, a mechanical speed multiplier is set in the transmission axis aimed at increasing the rotational speed of the rotor to adapt this turning speed to that of the generating electrical machine.

Braking system

Almost all turbines include mechanical brakes along the transmission axis. In many cases, apart from stopping the rotor from turning when this is out of service, the brakes are able to stop the rotor under adverse metereological conditions. Two types of breakes are normally used: disc brake and friction brakes.

Orientation system (Yaw)

This system helps rotate the nacelle so that the rotor is always in a transverse position respect to the wind with the aim to maximise the capture efficiency. The wind direction and speed are continuously controlled by anemometers and sensors located in the nacelle deck.

Orientation system (Pitch)

This systems lets the blades turn some angle over its longitudinal axis, known as pitch angle. With the variation of the pitch angle the aerodynamic coefficients of the blade that are totally related to the power capture of the turbine are modified. This system is used to maximise the power capture at lower speeds than the nominal and work as aerodynamic brake when the wind speed is higher than the nominal speed.

Transformer

The power output of the turbine is generally at low voltage and must be converted into medium voltage by a transformer to reduce transmission losses. The transformer is set up in the nacelle or the tower base.

Generator

Asyncronous generator: It is mainly a three-phase induction motor. If the mechanical torque working on the rotor axis is able to increase the turning speed up to going over the syncronism speed it then becomes a generator that supplies energy to the grid. These generators are used for systems where the turning speed is fixed or where back to back converters are available. Except in the case of big power machines, where their use is frequent in doubly fed configuration (Doubly Fed Induction Generator), its configuration is as rotor machine in squirrel cage, what avoids brushes and reduces the maintenance needs, making the machines much stronger.

Syncronous generator: With this type of generator, the energy produced is directly proportional to the rotor rotational speed, thus allowing variable speed. They usually go together with a Full Power Converter.

The current trend is to use machines with a high number of poles and a reduced aspect ratios to avoid the need to add mechanical reducers, which are expensive equipment of complex maintenance.

Converter (Full Power Converter)

In current systems with variable rotor speed, a frequency converter is placed between the alternator and the grid, which first transforms the variable frequency current from the alternator (as depending on the rotor speed, i.e., the wind) in Direct Current (DC) by a rectifier, and next reconverts the DC into Alternating Current (AC) to the grid frequency by means of an inverter. The frequency of the generated current gets thus independent from the grid frequency, what can also makes it possible the multiplier cancellation.

Power protections

This is a group of automatic switches endowed whose aim is to protect the installation against abnormal working conditions that may damage the turbine power system: short circuits, overloads, etc.

2.1.1.3 Components distribution

The different components for the large-scale wind turbines are set inside the turbine nacelle (Figure 3) unlike the different components of the small wind, as the following section will explain.

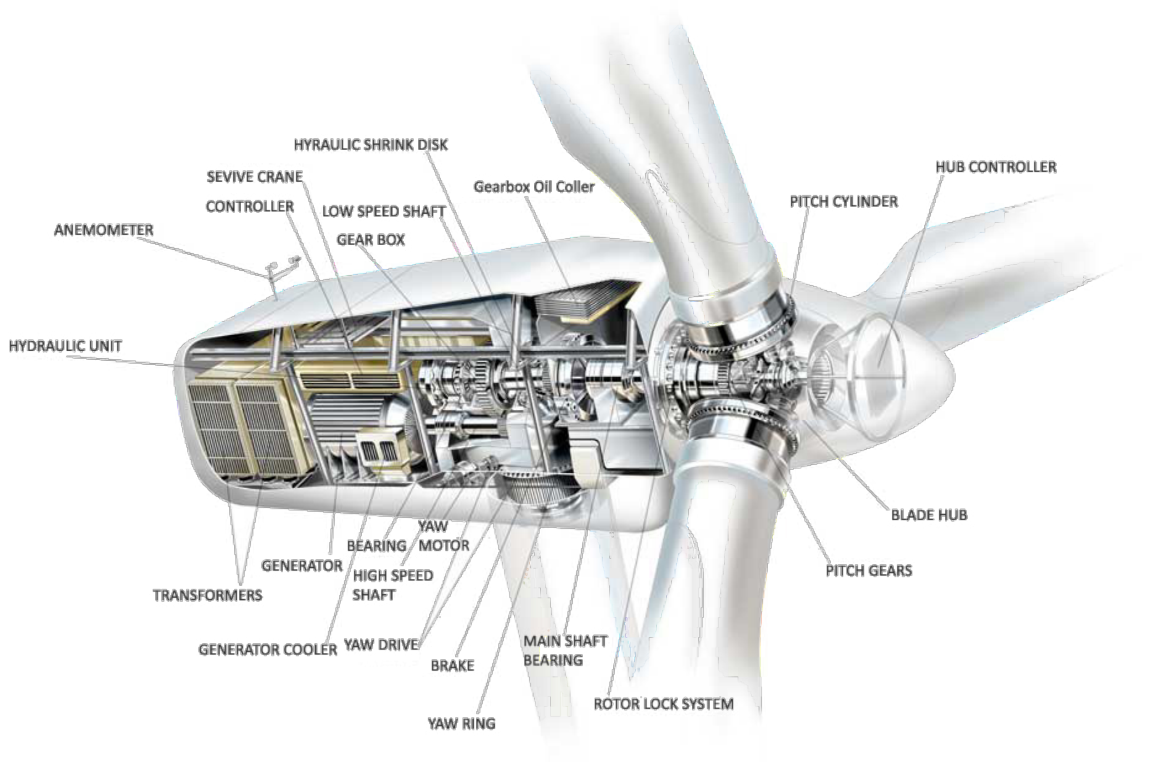


Figure 3.- Distribution of the main elements of a tri-blade turbine.
Source: https://www.renewableenergyhub.co.uk/

2.1.2 SMALL-SCALE WIND ENERGY

The power generation of these turbines and their dimensions are much lower than those of the horizontal axis turbines described in the previous section, being it possible to locate them in urban areas and in the surroundings of the highways network. The small-scale wind turbines are those with power output below 50kW, being the possible configurations and turbine components those reported next.

2.1.2.1 Turbines

The main typologies of small wind turbines, called micro turbines, found in the literature are: Savonius, Darrieus, Venturi, three-bladed and Vortex.

Vertical axis turbine type Savonius

This type of turbine mainly consists of two or four vertical plates (without airfoil profile) curved as half cylinders. By lacking the airfoil profile the torque that the half cylinders supply to the axis is due to the drag force. This is the reason why the efficiency of these turbines is much lower in relation to the turbines where the torque is generated by the lift forces. This type of turbines do not need orientation system and their turning speed is low (Figure 4).

Vertical axis turbine type Darrieus

The turbine is made up of two or three blades of airfoil profile curved and assembled to the main axis. Unlike the Savonius type, the Darrieus are lift force turbines so that their efficiency is much higher (Figure 5). The great disadvantage that they present is that their starting torque is null independently from the wind speed so they need an auxiliary starting mechanism. They do not need orientation system and their generating capacity is much higher.

Figure 4.- Savonius type turbine

Figure 5.- Darrieus type tubine

Horizontal axis turbine type Venturi

These turbines are conformed of six half circle blades forming a spherical construction. In general, the wind turbines can only harness the wind energy that is perpendicularly supplied to the rotor plane. The Venturi turbines create a turbulent flow that generates a low pressure area within the sphere, so that the surrounding air tends to get into the sphere. Once the rotor has captured the energy from the air, the air low in kinetic energy goes out and is dragged by the surrounding air flow. It is necessary to point out that, for a Ventury design, the turbine captures more air than the front area projected from the rotor plane. This helps to generate power from turbulent flows and from low speed winds (Figure 6).

Horizontal axis three-bladed micro turbine

These turbines are characterized by having rated powers ranging 1 to 20 kW. The start of these turbines does not need external means. The power generated by them is very sensitive to changes of wind direction. To compensate the changes of direction these devices are self-oriented by the joint operation of vanes and the Yaw mechanism, which helps the machine to rotate respect the vertical axis adjusting perpendicularly the impeller plane and the wind flow. In general, these devices do not have systems for power regulation based on the Pitch optimization, and the maximal power is produced for an only wind speed. The wind turbine is mainly formed by the turbine and the generator assembled to a multiplier. The mechanisms converter-transformer for energy conversion are external to the device.

Turbine type Vortex

In the last years new technological solutions far away from the conventional approaches have turned up. The Vortex is composed of a stiff cylinder designed to spin, thus eliminating the mechanical elements that may suffer wear or damage like the multiplier box of other wind turbines. This bladeless turbine captures the energy from the wind by a resonance phenomenon called vortex shedding. In fluid mechanics, when the wind passes through a blunt body, the flow is modified and a cyclic pattern of vortices is generated. Once the frequency of these forces is close enough to the structural frequency of the body, this starts oscillating and goes into resonance with the wind. Electrical power is generated through an alternator system, integrating spools and permanent magnets adapted to the equipment dynamic, without gears, axis or slidings. These turbines have lower efficiency than those previously commented on of vertical axis vertical (Figure 7).

2.1.2.2 Main components of the small wind

The small wind turbines share the following components with the large-scale turbines: **turbine, multiplier, axis, generator, converter/transformer, orientation and braking systems, tower/support structure and power protections** (Figure 7). The main difference is found in the size, complexity, power and location. In this type of turbines the generator is usually assembled to the turbine which is in turn rests on the tower. The rest of components, unlike the large wind, is usually set out of the turbine as shown in Figure 8.

Figure 6.- Venturi type turbine

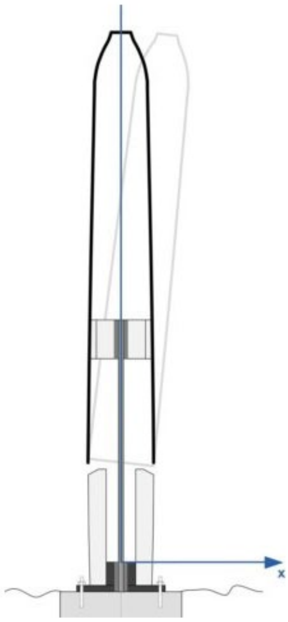


Figure 7.- Vortex type tubine

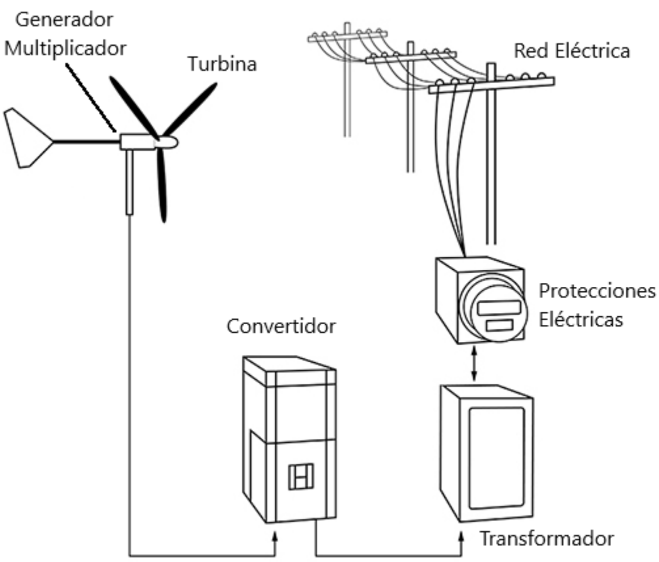


Figure 8.- Distribution of main elements of the small wind systems

2.1.2.3 Selection of small wind turbines

The proper choice of a small-scale wind turbine is not an easy thing, as several important factors have to be considered. The following are those on which the selection of the wind turbines mainly depends:

- **Regulations**: national, regional and local regulation (if any) have to be acknowledged in order to find out the conditions in which the installation and exploitation of small turbines is possible.

- **Wind resource and wind characteristics**: for the location of the small turbines, good enough wind resource has to be available that justifies the investment. For this, the onsite monitoring should include not only the amount of resource but also the type of wind at the position where the small turbine would be placed (more laminar or more turbulent wind).
- **Location and area needed**: along with wind speeds and directions, current and foreseen obstacles such as trees or buildings have to be carefully considered in order to avoid turbulence generated by them. According to the Catalogue of Small Wind Turbines (2016), developed by the Chinese Wind Energy Association and the Nordic Folkecenter for Renewable Energy, small turbines have to be sited 10 m above any obstacle within a 100 m horizontal radius.
- **Energy use, size and contribution by the small turbine**: the loads connected and the availability of energy storage or grid coupling with feed-in tariff will set the energy to be produced and the contribution of the wind turbine to the energy consumption. The actual size required will depend on the final application: less than 1 kW for basic applications such as charging batteries for minor devices; 1 to 10 kW for residential applications; and 10 to 50 kW for small and medium industrial applications.
- **Type of turbine**: small horizontal axis turbines are the most widely used. They are more efficient and therefore, can capture more energy per swept area. On the other hand, vertical axis turbines are less sensitive to the turbulences from obstacles than horizontal turbines and can be installed in places where the space is limited.
- **Other factors**: potential vibrations in elements nearby; potential noise impact on residential areas around; quality provided by the manufacturing companies in terms of performance and safety; or installation costs, are among other the factors that should be considered for the selection of small wind turbines.

2.1.3 COMPARISON OF PERFORMANCES

The maximum theorical efficiency that a turbine may reach is approximately 59%. This value is known as **Betz Limit** and it means that the maximum power that an ideal turbine is able to capture from the wind is 59% the available wind power, always fulfilling the following relationship:

$$P_{Extracted} \leq 0.59 \cdot P_{Available}$$

So the turbines performance called Power Coefficient $\boldsymbol{C_p}$ will always be lower than the Betz limit and will depend on each technology.

It is difficult to compare the performance of the different turbine typologies because these vary largely in size, constructive aspects and type of power adjustment. For this, an airfoil parameter that defines the type of turbine, TSR ***"Tip-Speed Ratio" λ***, is used. This helps us to compare the turbine performances and it is defined as the quotient between the tangential speed V_t in the blade end (of radius R and angle speed Ω) and the wind speed V_1.

$$\lambda = \frac{V_t}{V_1} = \frac{\Omega \cdot \mathrm{R}}{V_1}$$

In Figure 9, the performances $\boldsymbol{C_p}$ of the horizontal and vertical axis technologies are compared based on the TSR. The green curve is the one representing the ideal turbine.

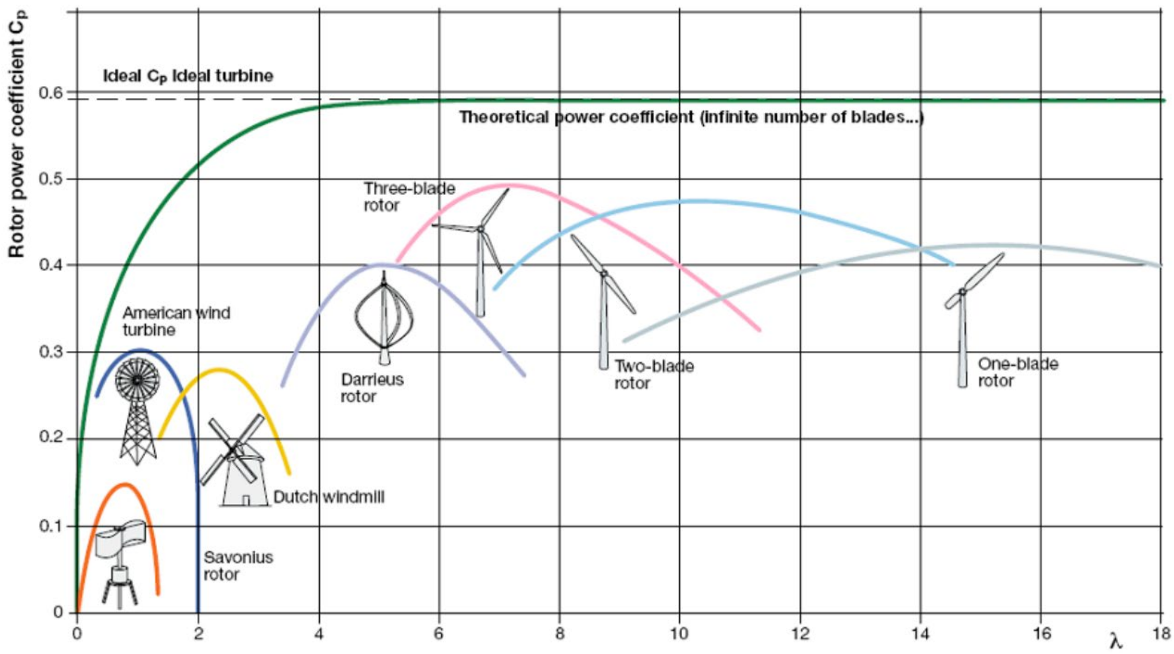


Figure 9.- Comparison of performances for different wind technologies. Source: ABB (2012)

Verifying that the horizontal axis turbines are more efficient than those of vertical axis (its $\boldsymbol{C_p}$ is higher) being the most efficient the three-blade turbine with a performance close to 50%. The curves $\boldsymbol{C_P} = \boldsymbol{f(TSR)}$ of the Figure 8 provide with the following information:

- There is one only TSR value for each curve for which the $\boldsymbol{C_p}$ is maximal, known as optimal TSR.
- The optimal TSR depends on the number of blades, the lower this is the faster the rotor must spin to maximise the capture of power.
- If the wind speed V_1 changes and the TSR must be kept constant and equal to the value for $C_{p,max}$ the rotating speed must also be changed. This gives rise to two types of turbines depending on the rotating speed Ω: turbines with fixed speed and turbines able to vary their rotating speed by an electrical converter. The latter are more efficient as they may adjust the TSR to maximise the power capture ($C_{p,max}$). They are mainly found in large-scale wind energy installations.
- The shape of the curve depends on each turbine, being flatter when the TSR is higher.

- Depending on the range of values TSR of each technology, the turbines can be classified into **slow turbines** for TSR lower than 5 and with performances between 15% and 40% (**mainly vertical axis turbines of small wind**) and **fast turbines** for TSR higher than 5 (**mainly horizontal axis turbine of large wind)** and performances between 40% and 50%.

In Figure 10, the performance of the same type of technology, in this case horizontal axis, is compared. As previously explained, when the number of blades is lower the turbine must rotate faster to reach the optimal TSR that maximises the Cp.

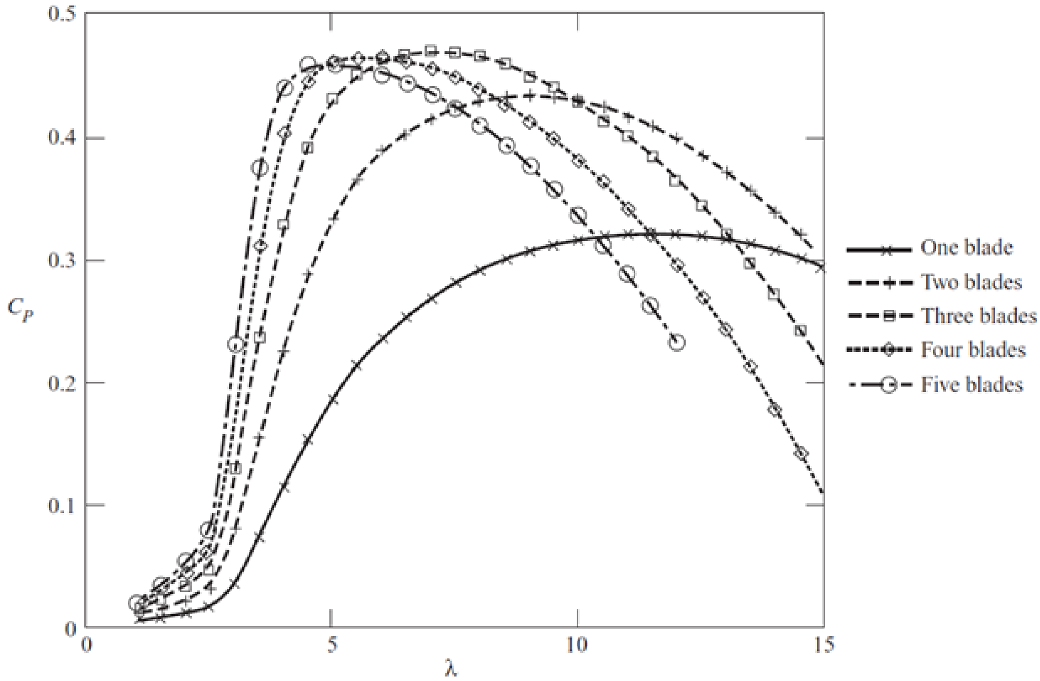


Figure 10.- Comparison of performances for horizontal axis performabce. Source: Letcher (2017)

2.1.4 LOCATION: SEPARATION AND DISTANCE CONSTRAINTS

The optimal location for wind turbines (looking always for favourable wind conditions and considering the separation among them) is an issue to take very much into account when placing them.

The **SEPARATION** among turbines is essential so that turbines placed behind others, *downstream*, are not affected by the turbulence that the front ones produce, *upstream*. This phenomenon is known as wake effect and if some distances are not observed the capture of energy may go down. In Figure 11 the power output of the *downstream* turbines is represented in black in relation to the separation (measured in diameters D) respect to the turbines *upstream*, while in blue the power capture ratio is represented. This means that when the distance between turbines is equal to 3 times the turbine diameter (3D) the capture power of the turbines behind is 30% of that of those placed forward. Therefore, the option is to place the downstream turbines between 7 and 10 times the rotor diameter so that the power fall is not that high.

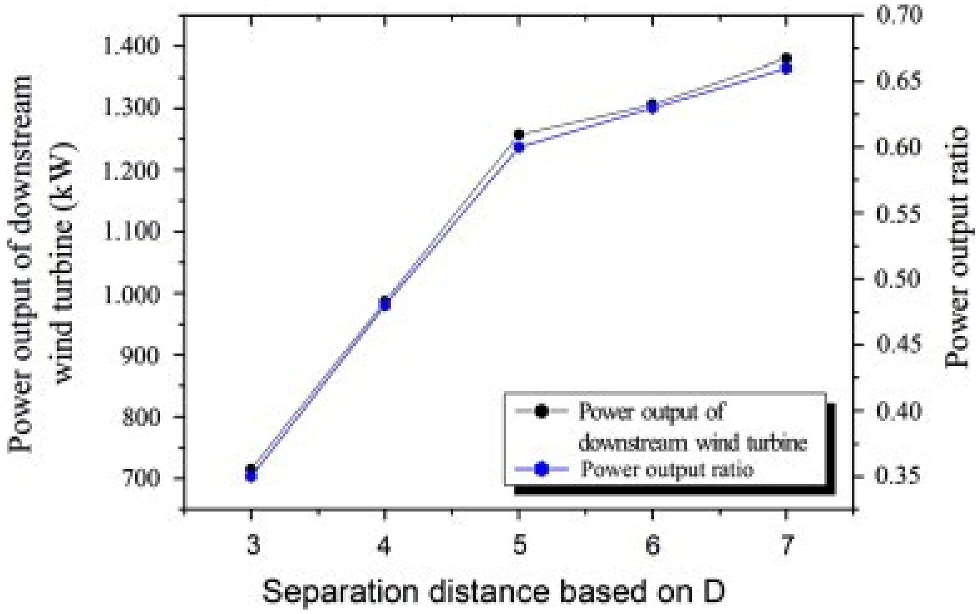


Figure 11.- Power output vs. Separation. Source: Choi et al. (2013)

Adjacent turbines placed perpendicular to the wind direction are not as affected so they can be spaced around 4-5 times de turbine diameter (Figure 12). In this sense, the bar plot in Figure 12 shows the results of a simulation analysis in which the influence of the arrangement of five turbines, 2MW each, in a wind farm is determined in terms of the wake losses and the topography affection. Thus, the five turbines facing the main wind direction were arranged in three different forms (M-shape, straight line and arch-shape) and two distances between them (5D and 2.5D). According to the results, wake losses (%) more than twice higher were obtained when the separation between turbines was reduced from 5D to 2.5D, with scarce influence of the arrangement (Figure 13).

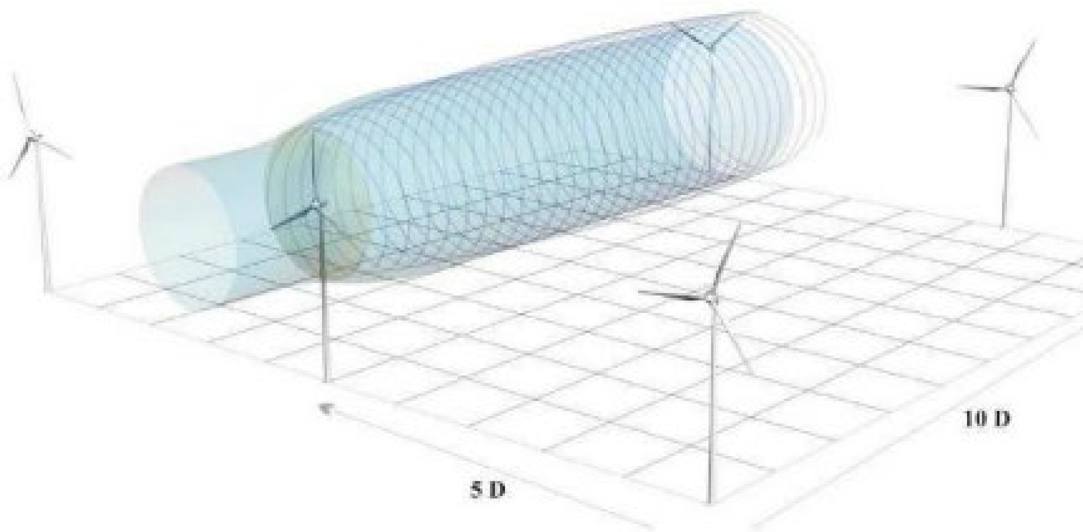


Figure 12.- Distance between turbines. Source: Schwanz et al. (2012)

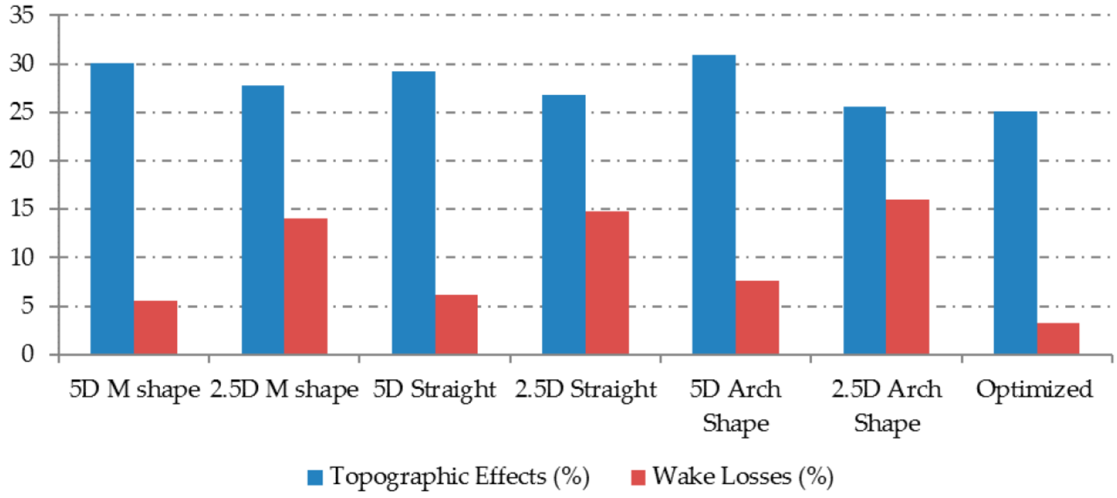


Figure 13.- Wake losses based on arrangement and separation of turbines. Source: Al-Addous et al. (2020)

In Table 1, the different technologies are compared, being the wind speed *"Cut in"* the necessary for the turbine to start producing electrical power and the *"Cut off"* the shut-down speed for strong winds that may cause damage to the turbine. The height H represents the distance from ground level to the centre of the Nacelle and the diameter D represents the rotor diameter (the cross sectional dimension of the circle swept by the rotating blades). Finally, the column "Spacing" estimates the separation (in relation to the diameter in previous column) so that the power harnessed from the wind is considered acceptable.

Table 1.- Comparison of wind energy technologies

Technology		**Power (kW)**	***"Cut in"* (m/s)**	***"Cut off"* (m/s)**	**Height H (m)**	**Diameter D (m)**	***Spacing [in number of diameters D]***
Large Wind	Three-blade	800-12000	3-3.5	20-25	50-180	40-150	4D-10D
Small Wind	Savonius	10	2.5	40	9	3	1-2D
	Darrieus	5-20	2.5	16	23	10	2-3D
	Venturi	2-3	3	18	5	1.3	1-2D
	Vortex	0.1	2	11	2.5	0.2	H/2
	Mini Three-blade	1-20	1.8	30	16	9.8	4D-10D

Some potential locations for wind energy harnessing along the road asset with large-scale and small-scale wind turbines are mainly the following: the rooftop of buildings or other structures, and in big areas such as parking lots, service areas, rest areas or proximities of the roadside. The use of wind energy harvesters in places where their performance can be affected by the turbulence generated by the vehicles (in traffic signals, in the refuge island, etc.) have been discarded for the purpose of the ENROAD project. The same applies to the use of small scale wind turbines for the harvesting of the energy from passing vehicles. In all these cases, the lack of reliable technical information beyond the different patents, designs or research papers mainly focused on small scale or basic numerical experiments, as well as their potential low energy output, makes these technologies not relevant enough for its actual installation, specially when compared to the more common uses of these turbines. More information about locations and topologies currently used by NRAs for the implementation of wind energy systems can be found in chapter 5, where a review of the current experiences has been done.

In what the installation of large-scale wind turbines (wind farm) aside of the road (Figure 14) is concerned, special attention should be paid to the noise generated by the turbine itself, the visual impact that these huge structures can cause to drivers, and specially the potential fall of ice from the blades or even of the blades themselves.

Therefore, it seems that the **DISTANCE TO THE ROAD** (and road network) is of key importance at the time of locating a wind farm. In this context, an evaluation of the minimum distance of the wind turbines to the highways was financially supported by the Danish Energy Agency and carried out by the Department of Wind Energy of the Technical University of Denmark in 2012. The study was based on a risk assessment of the consequences of total or partial failure of a wind turbine and of the ice fall in case of over-icing.

Figure 14.- Wild Horse wind farm (Washington). Source: Wild Horse (2014)

Under the assumption of a row of wind turbines along a highway with total height of 120 m and a spacing of 400-500 m, results showed that given a probability equal to $2 \cdot 10^{-9}$ that a person looses his/her life in a highway, this generally accepted risk on highways is increased in less than 0.14% when wind turbines are installed more than 100 meters away from the highway. According to the analysis, the height and distance between them is of less importance in this context. On the other hand, under the assumption of tip heights of 150 m and spacing of 400 m, the generally accepted risk on highways in increased with less than 0.1% when the turbines are installed more than 150 meters away from the highway. The risk is slightly greater when the turbines is in operation. All in all, even if the risk seems to be low when the turbines are installed far enough, a proper risk assessment should always be performed including the location in relation to the road and the prevailing wind direction.

Noise from wind farms very close to the road might not be such a serious risk for drivers life but it is still a source of discomfort and therefore, a safety issue. A study carried out in 2016 suggests that the noise from wind turbines is considered 17–18 dBA worse than road traffic noise by people living nearby, while other study from the same year suggests that communities are between 11 and 26 dB less tolerant of wind turbines than of other transportation noise sources. Other studies address the issue of the distance of the wind farms from the road in this sense. These are neither experimental nor numerical studies on wind energy but methodological approaches for the evaluation of wind energy potential and the decision making on optimal planning of wind farms. Thus, both the technical review paper carried out in 2021 by reasearchers of the Federal University of Santa Maria (Brazil) and the techno-economic feasibility analysis performed in 2018 by researchers of the Akita and Kyushu Universities (Japan), cover the suggestions of different authors by stating that wind farms must be at least 500 m away from the main road network as otherwise the wind turbines might affect road transport due to the loud noise and the shading generated by blades. Anyway, it seems that the noise annoyance might depend also on other factors such as visual or aesthetic factors. A bad attitude towards the wind farms might then play a role, as this could not be separated when asked about the noise. Less stringent criteria is followed by the *Consensus based Siting tool suite (ConSite)* developed in 2018 by investigators of the Norwegian Institute for Nature Research (NINA) and Norwegian University of Science and Technology (NTNU) for the optimal location of onshore wind-power plants. Also aimed at helping to structure decision problemas and identify decision strategies, the distance from wind farms to main roads set by ConSite siting tool ranges from 100 m (least acceptable) to 300 m (most acceptable). The weight of this criterion in the tool is noteworthy: 30% over the technical criterion (20% partial weight) and a very representative 6% over all criteria. Finally, an interesting work in this same line carried out in 2015 by researchers of the Royal Institute of Technology (Sweden) considered that a 200 m buffer zone around national roads should be excluded as sitting area for wind farms.

Keeping a certain distance to the road is thus something to be seriously considered when it comes to the safety of the drivers and the noise generated. Nonetheless, in order to come up with a robust siting of the wind farms logistics needs to be considered too, which makes the decision on the distance a contradicting question. Thus, wind turbines should be as close as possible to the main roads to reduce the construction and maintenance costs mostly associated to the longer time needed for carrying the materials, the longer distance covered by the construction equipment (extendable flatbed trailers, cranes, concrete trucks, etc.) and the more difficult access to the construction site. Regarding the latter, longer and more rugged terrain between the main road and the wind farm will result in longer distances covered over lower quality tighter roads and the need for more challenging access roads. Therefore, the proper selection of the access route is essential for the overall planning of the wind farm construction, in particular when long distances exist from the paved road.

A document prepared by the company Nordex SE, very well-known European designer and manufacturer of wind turbines, provides the main requirements for an access road when K08 delta wind turbines with 3-4 MW power output are built. May this specific case serve to establish the miminum general requisites per wind turbine:

- The access road for wind turbines must be capable of supporting loads from concrete trucks and construction vehicles (50-100 approx.), heavy trucks for crane erection (15-40 approx.) and heavy trucks with turbine elements (8-11 approx.).
- The acces road must be capable of accommodating 73.5 m maximum length trucks for rotor blade transport and 49 m length for tower transport. Truck width of up to 12 m might be necessary for the transportation of crawler cranes.
- Slopes of approx. 10-12% for ideal road and weather conditions should not be exceeded unless it is previously consulted. For steeper slopes, additional tractor units and pushing vehicles can be used provided that suitable surface conditions exist.
- Minimum vertical radii in crests and valleys have to be achieved or otherwise on-site inspection must be performed to discuss potential alternatives.
- On access roads to the construction site a 5-6 m clearance height and a 5 m clearance width must be at least ensured, depending on the project and location.
- Enough area has to be available on the access roads for providing the wind turbines elements the space required in the different curves.
- In terms of the road construction: site-specific ground conditions must be taken into account for defining the load-carrying capacities; all the layers and the subsoil must be properly compacted to allow heavy vehicles traffic; and proper drainage must be ensured (cross slope of 1 to 2%).

Finally, a minimum distance to other important energy and transport infrastructures and urban areas has to be maintained for safety reasons. Because of the possible proximity of these infrastructures to the road assets, some observations are provided following.

The turbulence generated downwind of the turbines due to the rotating blades is a safety challenge that needs to be addressed especially in the case of small airfields as they can affect small and light aircraft. Most countries deal with this risk by a applying a certain (large) distance between the wind turbines and the aircraft. For instance, a law in 2015 by Oklahoma Governor Mary Fallin set a minimum mile and a half (≈2,414 km) distance from airports for new wind energy farms. Actually, that law stated that any tower could not be closer than that distance from a public-use, private-use, or municipal airport, a public school, or a hospital. Increasingly higher towers have also become physical obstacles that can be dangerous to low-flying aircraft. Therefore, the so called Obstacle Limitation Surfaces (OLS) around small airfields need to be adequately addressed, even though measures against the induced turbulence are often considered more restrictive than obstacle clearance requirements.

So as said before, keeping a conservative **DISTANCE FROM THE AIRPORTS** is now the common solution to mitigate the impact of wind farms on these transport infrastructures. In this sense, the technical literature consulted, which is mostly again decision support systems for wind farms planning, establishes minimum distances of 2500 and 5000 m. Also in this regard, the Guidebook for Energy Facilities Compatibility with Airports and Airspace (2014) it worth highlighting. This is an Airport Cooperative Research Program report by the US Transportation Research Board on the compatibility of energy facilities and airports. Much more conservative distances are here recommended. Thus, according to this reference book taller wind turbines should be no closer to an airport than 7 nautical miles (≈ 13 km), medium ones no closer than 3.6 nm (≈ 6,67 km) and smaller ones no closer than 1.8 nm (≈ 3,33 km). Overall, it seems that optimum the distances between the airports and the widn farms have not been determined yet.

But wind turbines are not only tall structures with moving parts potentially risking low-flying aircraft. More importantly, they are electrical equipment that generate electromagnetic radiation that may interfere on Communications, Navigation and Surveillance systems used for Air Traffic Control (ATC) such as the radar or the VOR (VHF Omni-directional Range). The latter is a short-range radio navigation system that provides bearing and distance information to aircrafts for a safer and more accurate and reliable navigation. Wind turbines can therefore affect the reliability of systems used by pilots for guidance in such a way that they can be potentially detected by Primary Surveillance Radars (PSR) and appear on ATC displays.

The differente National Aviation Administrations and the Departments of Defense and Homeland Security in the whole world make use of the radars every day to track everything from weather patterns to aircraft, including national security threats. The basic principle behind radars is simple: it sends out short pulses of radio waves, which bounce off any object in their path and return to the radar. These radar systems detect the size and location of different features in its line of sight by measuring the strength of the radio waves reflected off them. And the impact of wind turbines on radars is in fact due to the way they process those signals. While most ATC radars are able to discriminate between echoes from stationary objects and from moving objects on the basis of the well-known *Doppler effect*, this capability is not enough to discriminate spinning blades, with speeds comparable to aircraft, from airplanes. Those unwanted echoes intercepting the radar signal such as those returning from moving blades (or ground, sea, etc.) are called ***clutter***.

Therefore, if radar displays become cluttered with undesired echoes from wind farms located close to the airports, air traffic controllers can find it more difficult to differentiate between genuine aircraft and wind turbines, this leading to uncertainty and potentially safety issues.

Main factors influencing the impact of wind farms on radar systems are: the **DISTANCE FROM THE RADAR** facilities and the wind farm; the height, size and number of turbines in the wind farm; and the age of the radar system. Fortunately, there are several solutions to mitigate the radar interference: keeping a certain distance between radar and wind farm; using special materials for the construction of the turbine blades; and updating software and specially hardware of nearby radar systems. As said before, optimum distances are still to be accurately determined. In terms of materials, radar absorbing treatments for blades mitigate radar interference, but while they do not eliminate it completely, these treatments pose a significant cost to wind farm developers.

Possibly, the most common technique for the mitigation of wind farm clutter is the *infill radar*. This system is about placing a new radar in a position where screening by terrain prevents it from being able to detect the wind turbines, while a full coverage of aircraft is provided (Figure 15). Examples of implementation of the infill radar are Glasgow International Airport, where the radar was installed in 2018 to minimise the impact of the new Kype Muir Wind Farm in South Lanarkshire; or the Kincardine radar, specifically placed to mitigate the impact of the Whitelee Wind Farm on the Primary Surveillance Radar of Glasgow Airport (first operationally deployed infill mitigation system in the UK).

Finally, in addition to roads, airports and communication facilities, a minimum distance from transmission lines and railway networks must be considered for safety reasons. On the other hand, the implementation of wind farms not only involve installing the wind turbines and building access roads, but also extending and connecting to power lines. Thus, while it is necessary to maintain a minimum distance from the power lines not to compromise the local network, their proximity decreases the high cost for implementing new lines and avoids energy loss due to the long distance between the generation and consumption site.

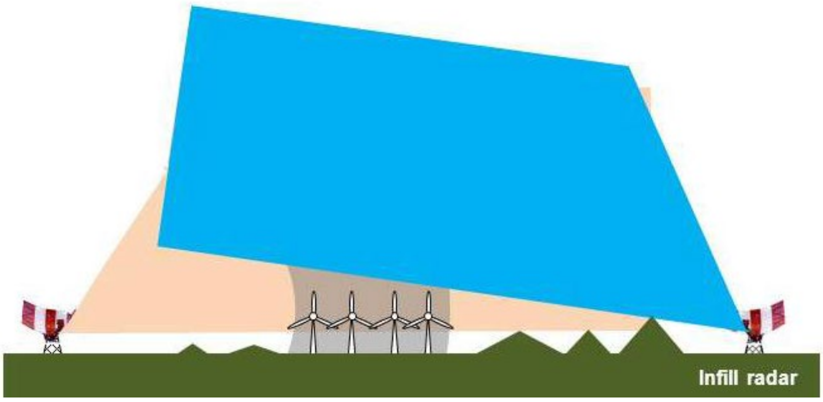


Figure 15.- Infill radar principle. Source: Jackson (2013)

The same sources used to explore the different recommended values of distances to the road have been used to look at the distance to the power lines. According to those documents, wind farms should keep a distance from overhead power lines of at least 200-250 meters. Regarding the *ConSite* siting tool (2018), the distance set is less restrictive, as it ranges from 150 m (leas acceptable) to 10,000 m (most acceptable). The weight of this criterion in the tool is noteworthy: 20% over the technical criterion (20% partial weight) and a representative 4% over all criteria.

Finally, similar to what happens with roads (to a lesser extent, though), it is recommended in the technical literature that a certain distance from rail networks is maintained for safety reasons. On the other hand, the distance from the rail network might reduce expenses in case of transportation by train of equipment for the wind farm or when the rail network is a final energy consumer. Based on the few references found, distances of 200-300 m should be set. As with other infrastructures considered above, optimum distances are not defined yet. Besides, specific conditions of the construction site must be taken into account.

2.1.5 CLEANING AND MAINTENANCE

To measure the payback profitability of a turbine, not only its design-construction and location have to be taken into account; failures in the components originated by the wear must be also considered. In order to mitigate these problems, maintenance strategies must be designed that are able to achieve the turbine availability. To get to know the failures in the components it is essential to rightly develop maintenance strategies.

In Figure 16, the frequency of yearly failure of the main components of the turbine can be seen in blue, while in red the periods of inactivity are represented. It must be highlighted that the electrical failures are produced with higher frequency than the mechanical, but in turn, the mechanical provoke longer stop periods than the electrical. In order to carry out the maintenance strategies, the types of maintenance known in the industry (corrective, preventive and predictive) should be employed, whose planning will reduce the failure frequency, operation costs and repair stops. Depending on the nature of the elements, two types of maintenance will be mainly distinguished: mechanical-structural and electrical.

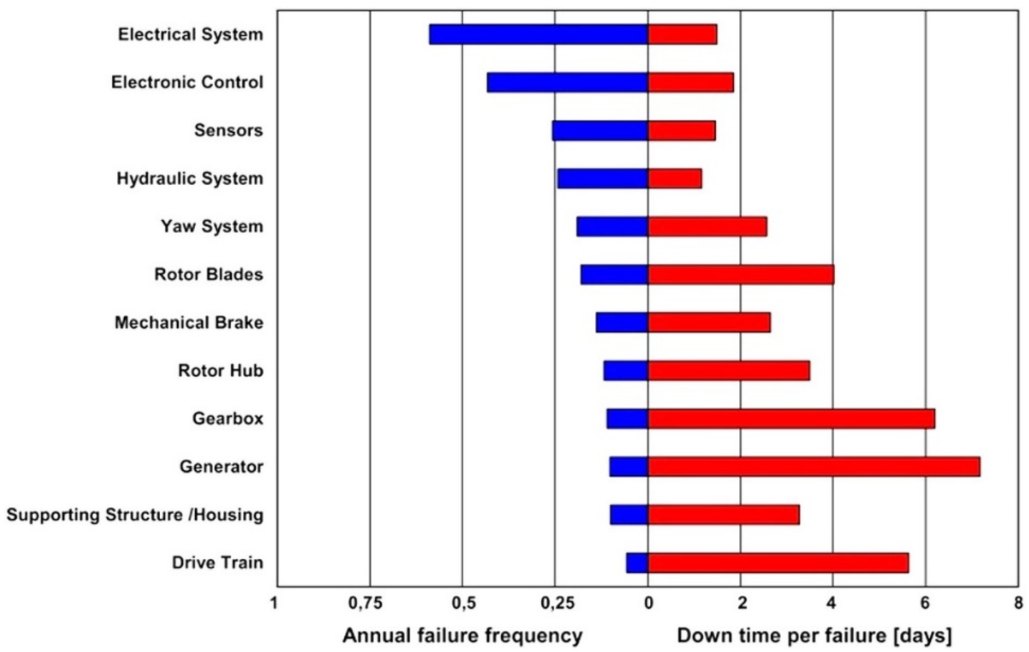


Figure 16.- Frequency of failure of the wind turbine components. Source: Hahn (2007)

Mechanical-structural maintenance:

- Detection of fissures or cracks in the hub or blades.
- Revision of the bolted joints and/or of the tensioning of the torques.
- Lubrication of pillows, supports and bearings. Hearing inspection of the orientation system.
- Oil analysis of the multiplier box.
- Revision of the levels of the hydraulic system.
- Hose state, leak and pipe inspection.
- Vibration measurement.
- Periodical revisions to evaluate the efficiency of the orientation systems Pitch and Yaw.
- Shank and blade clean-ups.
- Periodical revisions of degree of wear of the bearing and pillows of the main axis, the orientation systems, multiplier and of the mixed systems such as the bearings of the electrical generator.

Electrical maintenance:

- Wiring inspection: it is important to verify that there are not terminals, cables and/or connections in bad shape to guarantee the right functioning.
- Verify that there is not any emergency switch interlocked and the signal and emergency pilots work properly.
- Change of brushes in the electrical machines and excitation systems. The brush, manufactured in graphite, makes the electrical sliding contact possible between the rotor of the machine and the external part.
- Check the correct functioning of the sensors and their feeding systems such as anemometers, vanes, acelerometers, temperature, pressure sensors, etc.
- Periodical measurement of electrical values, voltage, power, phase syncronism, level of harmonic supplied to the grid, in the generator, converter and transformer.
- Check the oil level and transformer oil dielectric analysis. Analysing the state of this oil it may be determined if the transformer has suffered any undesired behaviour such as overloads, partial discharges, short circuits, etc.

2.2 SOLAR PV ENERGY

Photovoltaic power systems transform the solar energy into electrical power direct and instantaneously by the photovoltaic effect, according to which semiconductor materials such as the silicon or germanium generate electricity when they are exposed to solar radiation. Main references used for the development of section 2.2 are: ABB (2011), Benick et al. (2017), Bhattacharjee and Saharia (2014), First Solar (2014), Green et al. (2018), IRENA (2019), Kayes et al. (2011), Komiya et al. (2011), Matsui et al. (2015), Mertens (2014), NREL (2021), Photovoltaics (2001), PVGIS (2012), REN21 (2020), Smets et al. (2016), Song et al. (2021), Sulaiman et al. (2014), Wu et al. (2018), Yang et al. (2015) and Yoshikawa et al. (2017).

This technology has experimented a global and exponential growth in terms of power (GW) installed in the last years, being the renewable energy that has presented the highest growth rate in relation to the generation of electrical energy. In Figure 17, the increase of the total power installed worldwide between 2009 and 2020 is represented, where China stands out after betting for this technology.

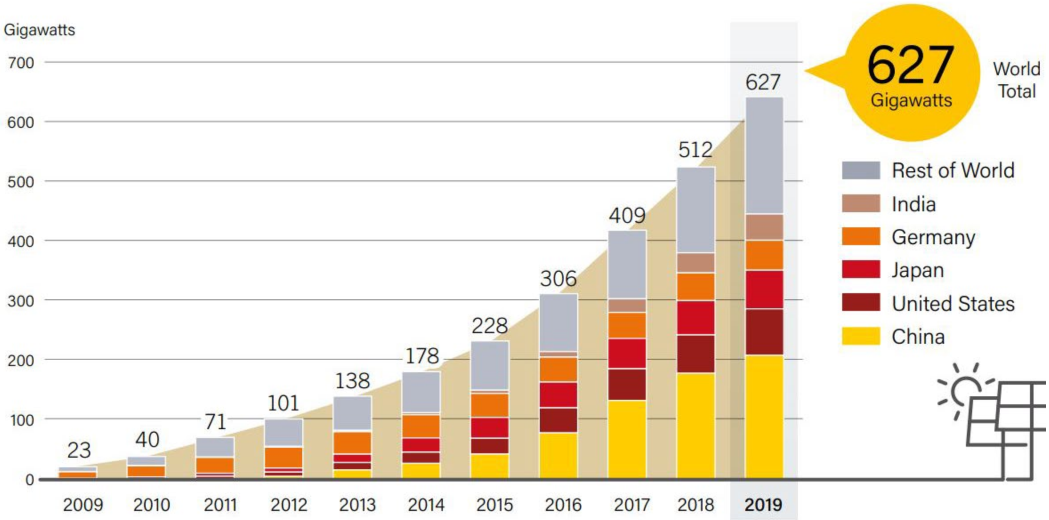


Figure 17.- Evolution of total power installed worldwide. Source: REN21 (2020)

It is interesting to analyse the perspectives that international organizations such as IRENA (International Renewable Energy Agency) have foreseen for the development of this technology (Figure 18). The growth is clearly increasing, the photovoltaic energy could grow up to almost six times during the next 10 years, reaching an accumulated power at world level of 2840 GW for 2030 and an increase of 8519 GW for 2050. This implies that the installed capacity in 2050 would be almost 18 times the installed capacity in 2018. According to this agency, around 60% of the total photovoltaic energy worlwide in 2050 will be generated in big concentrated photovoltaic installations, with the remaining 40% in distributed installations.

The electricity generated by the photovoltaic panels depends mainly on:

- The **solar radiation** incident on the installation place.
- The **orientation of the panels** and the presence or not of shadows.
- The **performance of the panels**, which is associated to the panel technology.

The incident solar radiation on the installation place is essential. In fact, the energy produced by the same photovoltaic cell placed in the north or the south of Europe is very different. Part of the energy produced by the sun reaches the earth´s atmosphere in the form of a **solar irradiance** (radiation power by surface unit) of approximately 1365 W/m^2. By passing through the atmosphere this radiation decreases due to it is partially reflected and absorbed by the water vapour and other gases. Once the atmosphere is passed through, the radiation is partially diffused by the air and the particles suspended on it.

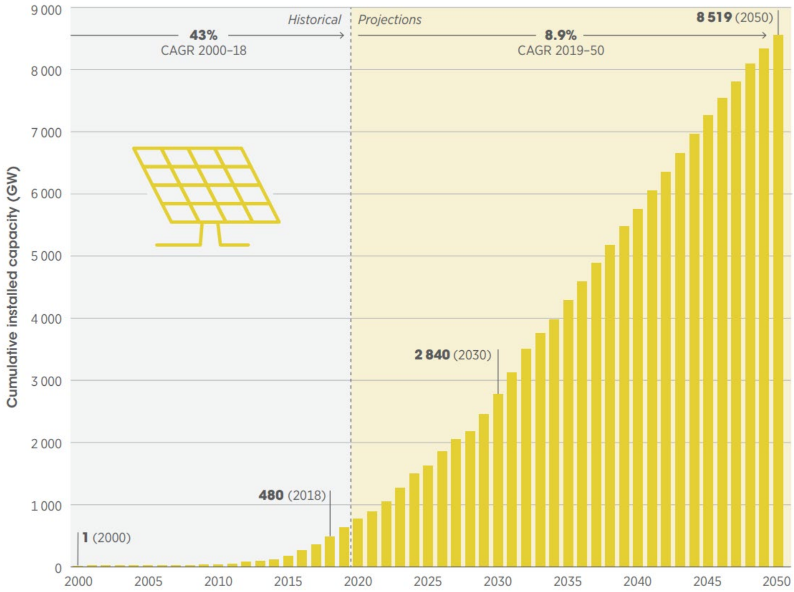


Figure 18.- Evolution of the power of photovoltaic energy installed 2000-2050. Source: IRENA (2019)

The energy that a PV panel can generate is determined by the **solar irradiation** (energy of the radiation by surface unit along a period of time). The solar irradiation is directly related to the latitude, decreasing as moving away from the Equator. In Figure 19, the annual irradiation map is represented as expressed in kWh/m^2 year. Germany stands out in this particular context, as being a country leader in PV energy while receiving a radiation significantly lower than in Spain, south of France or Italy.

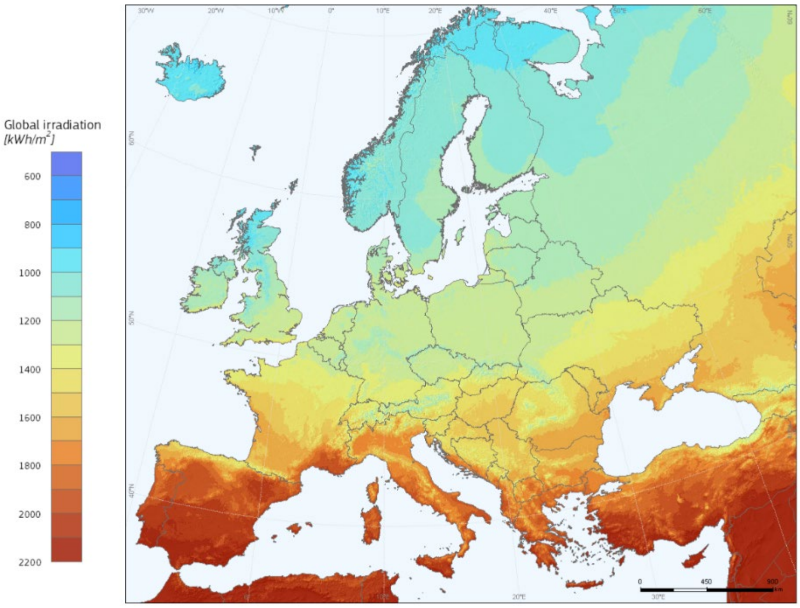


Figure 19.- Map of solar irradiation in Europe (kWh/m2 year). Source: PVGIS (2012)

2.2.1 MAIN COMPONENTS OF A PV POWER STATION

2.2.1.1 Photovoltaic power station

The main component of a PV generator is the **photovoltaic cell**, where the conversion from solar radiation to electrical power takes place. Cells are mainly composed of a semiconductor PN junction. Understanding doping as the possibility to vary the number of valence electrons of the semiconductor material, two main types of doping exists:

- Type P: The silicon with four valence electrons is doped with atoms of three valence electrons such as boron (positive doping), giving rise to the layer type P.
- Type N: The silicon with four valence electrons is doped with atoms of five valence electrons such as the phosphorus (negative doping), giving rise to the layer type N.

Due to the nature of the PN junction, without applying external energy it is not possible the circulation of power between these two layers (there is no flow of electrons between the layers). When the cell is exposed to the light the photovoltaic effect is produced, the electrons capture energy from the outside being this able to circulate between both layers. By connecting to this junction an external conductor a closed circuit is obtained, in which the voltage flows from the layer P (with a higher potential) to the layer N (with a lower potential), provided the cell is illuminated. This process is represented in Figure 20.

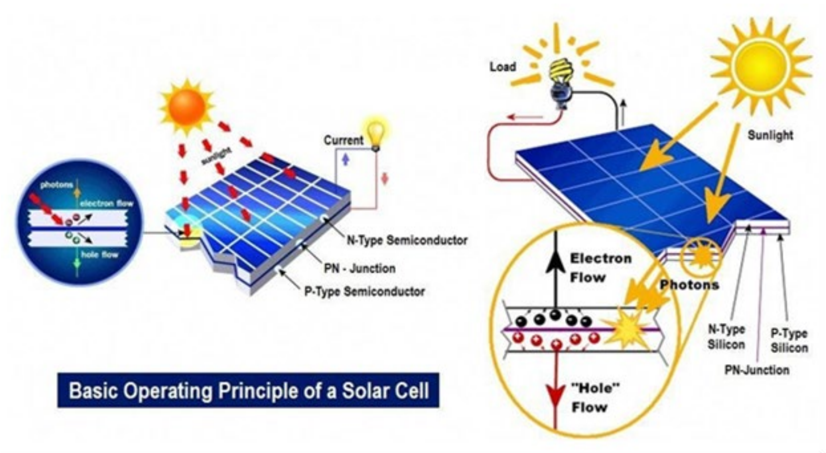


Figure 20.- Basic operation principle of a solar cell. Source: www.electricaltechnology.org

The standard values voltage-power that a photovoltaic cell generates for an irradiance of 1W/m^2 are approximately 0.5 V and 3.0 A. To increase the generation power (P = V*I) the cells are associated with connections: series (to increase the voltage) and parallel (to increase intensity). Normally, **photovoltaic modules** are commercialised as formed by a group of cells with series-parallel connections, which depend on the type of module. Several modules connected give place to a **photovoltaic panel** and several panels connected in series form an **array**. Finally, several arrays in parallel form a **photovoltaic power station**, solar farm or solar power plant. The different elements described are represented in Figure 21.

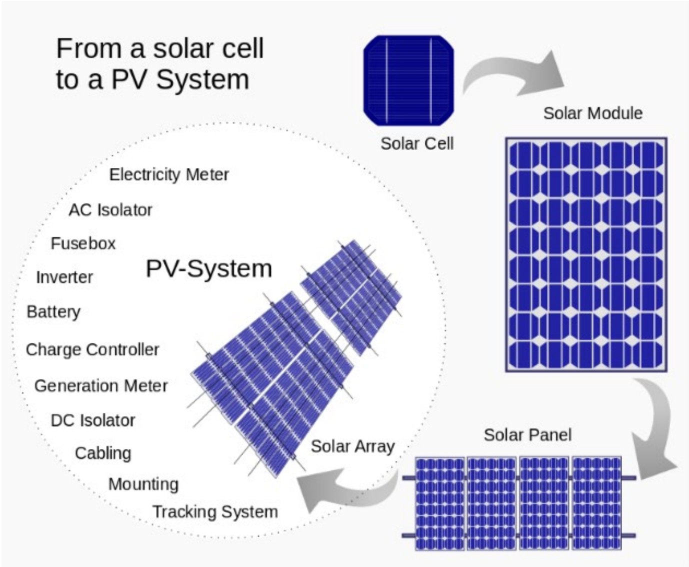


Figure 21.- Elements that compose the photovoltaic system. Source: Wikipedia.

TECHNOLOGIES OF PHOTOVOLTAIC CELLS

There exists a number of photovoltaic cells depending on the materials employed in their construction. A fast and efficient way to compare the different technologies is by their performance, taking this as the relation between the power produced by the cell $P_E(W)$ respect the power of the solar radiation $P_R(W)$ available. The solar radiation power will be equal to the product $I \cdot S$, being I the irradiance (W/m^2) and S the surface (m^2). The performance of a PV technology is thus calculated according to the equation:

$$\eta = \frac{P_E}{P_R} = \frac{P_E}{I \cdot S}$$

On the other hand, depending on the materials and the technology employed the photovoltaic cells can be classified into four big groups.

Si crystalline: _Si cells_

Currently, this type of panels are the most used, their thickness normally being between 100 and 200 μm. Depending on the type of silicon crystal there are two types of cells: mono and polycrystalline silicon cells. The monocrystalline silicon cells are formed of high quality silicon. They are obtained from the growth of a uniform crystal, present high performance and have a high cost. The cells of polycrystalline silicon are formed by silicon of a lower quality compared to the monocrystalline silicon, composed by aggregated crystals. This type of cells present a lower performance and cost. Both technologies reach approximately 90% of the world market of PV cells.

1. **Monocrystalline silicon**
2. **Polycrystalline silicon**

Thin-Film Technologies

These technologies are formed by thin films of semiconductor micron-thick material. Due to this, the savings of material respect to the silicon technologies is very remarkable. These cells, unlike the previous ones, are very flexible, this incrementing their field of application. In relation to the materials used, the cells can be:

1. **Amorphous silicon**
2. **CdTe, Cadmium Telluride**
3. **GaAs, Gallium Arsenide**
4. **CIGS, Copper, Indium, Galium and Selenium**

Multijunction cells

These cells are formed by multiple PN junctions. Each junction produces an electric current responding to the different longitudinal waves of the radiation, what dramatically increases the performance. Today, the extremely high cost and high relation cost/efficiency have limited the use of this technology to very concrete sectors such as the aerospace where giving priority to the relation efficiency/weight comes first independently from the cost. These cells can be:

1. **Two junction cells.**
2. **Three junction cells.**
3. **Four junction cells.**

Emerging photovoltaic technologies

This type of technologies are still in research stage and under constant development. The cells sensitized by dyes (Dye sensitised), the Perovskite, organic cells and “quantum dot” cells stand out the other:

1. **Organic cells.**
2. **Perovskite cells.**
3. **Dye sensitized.**
4. **Quantum dot cells.**

In Figure 22, the highest performances for the different photovoltaic technologies are represented (under lab conditions), traced from 1976 to the present according to the National Renewable Energy Laboratory. In Table 2, the main technologies for the four groups described above, with their associated performance and bibliographic references are summarised. In Table 3, pros ans cons of these technologies are defined.

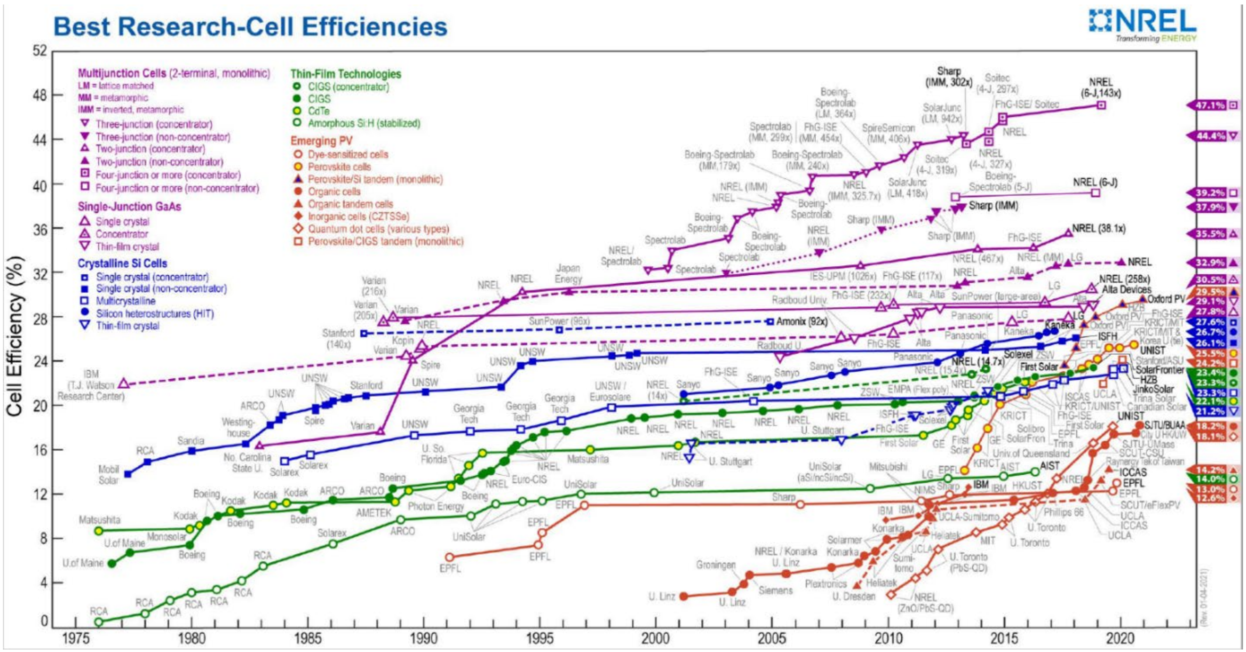


Figure 22.- Evolution of the performance of PV technologies between 1976 and 2020. Source: NREL

Table 2.- Comparison of maximum performances in laboratory for the different photovoltaic cells.

Technology		η_{max} %	Literature Ref.
Silicon Crystalline Si-cells	Monocrystalline Silicon	26-27	NREL (2021); Yoshikawa et al. (2017)
	Polycrystalline Silicon	22-23	NREL (2021); Benick et al. (2017)
Thin film Thin-Film Technologies	Amorphous Silicon	10-14	NREL (2021); Matsui et al. (2015)
	CdTe	21-22	NREL (2021); First Solar (2014)
	GaAS	28-30	NREL (2021); Kayes et al. (2011)
	CIGS	23-34	NREL (2021); Wu et al. (2018)
Multijunction cells	Two junction cells	33-35	NREL (2021)
	Three junction cells	38-44	NREL (2021)
	Four junction cells	39-47	NREL (2021)
Emerging PV technologies	Organic cells	11-12	Green et al. (2018)
	Perovskite cells	22-25	NREL (2021); Yang et al. (2015)
	Dye sensitized	12-13	NREL (2021); Komiya et al. (2011)
	Quantum dot cells	18	NREL (2021)

Table 3.- Pros and cons of the most currently used technologies.

Technology	Pros	Cons
Monocrystalline Silicon	Very High η, η constant, very mature and reliable technology, medium-low environmental impact	High production cost, complex production process.
Polycrystalline Silicon	η constant, medium-low production cost, medium-low environmental impact, simpler production process.	The performance is not as high as the monocrystalline silicon
Amorphous Silicon	Low production cost, simple mass production, influence of the reduced temperature.	Low performance, little stability and bigger measurements.
GaAS	η very high, great resistance to high temperatures.	Very high cost of production, toxicity and availability of materials.
CdTe	Low production cost, high η.	Toxicity and availability of materials.
CIGS	Medium and very constant performance, low production cost, good performance in low radiation conditions.	Toxicity and high environmental impact.

The photovoltaic cells are generators of continuous DC current. Their I-V characteristic curve (in blue) and the power curve (in red) for a certain irradiance are shown in Figure 23. The power curve is the product I·V. In general, it is important that the panel works in the working point of maximum power P_{max} or optimal working point M_{pp}. This situation is in the point $(V_{Pmax,}I_{Pmax})$.

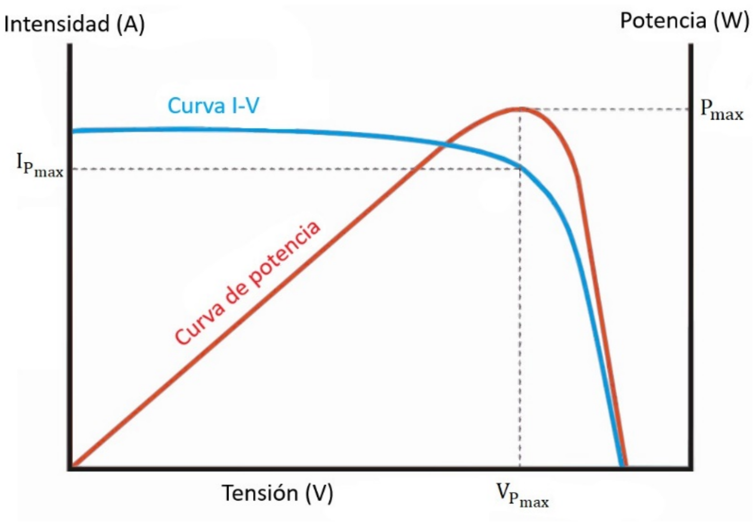


Figure 23.- Characteristic I-V and power curve of a photovoltaic cell

When the irradiance increases, the curve I-V is vertically *displaced* (Figure 24), thus increasing the intensity proportionally. The voltage variation without charge is minimal and conversion efficiency is not affected by the irradiance variation within the operating values of the cells, what means that the cell performance is the same for a sunny than for a cloudy day.

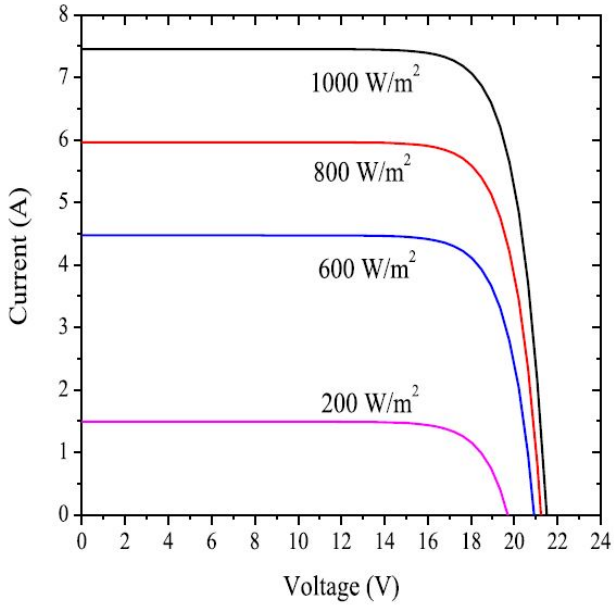


Figure 24.- I-V curves for different irradiances. Source: Bhattacharjee and Saharia (2014)

2.2.1.2 DC/DC Converter

This element is usually employed in isolated installations. The main objective of a DC/DC converter is to make the output voltage independent from the load. In Figure 25, an installation without DC/DC converter is shown. In green the photovoltaic panel is represented and R would be its charge. The possible working points mark the intersection between the curve I-V and the line of the charge in black (it is a resistive load, otherwise it would not have a linear behaviour). As it may be verified the working points are far from the points M_{pp} (maximum power).

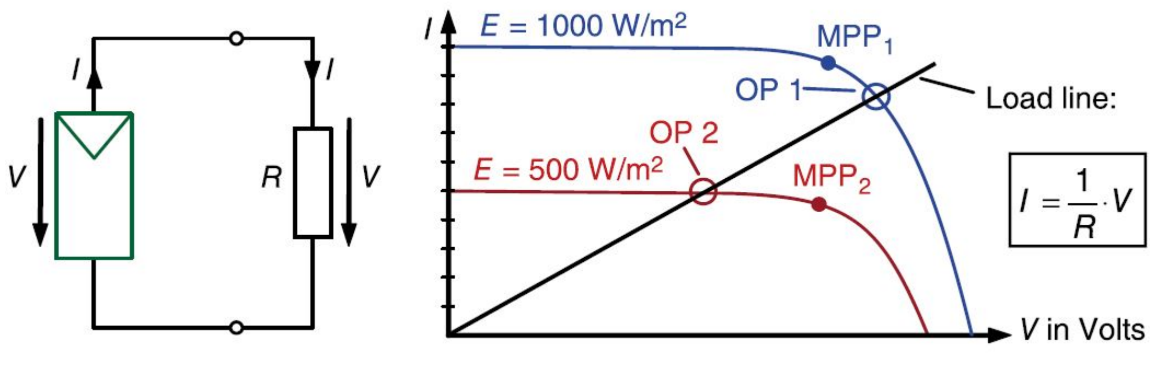


Figure 25.- Installation without DC/DC converter. Source: Mertens (2018)

In Figure 26 an installation is represented in which a DC/DC converter (blue) is inserted between the load with voltage V_2 and the panel with voltage V_1. When working with constant voltage, if the irradiance varies it is possible to be closer to the optimum working points. Another advantage of the DC/DC converters is the capacity to increase the voltage to avoid losses by voltage drops. The performance of this equipment is above 95%.

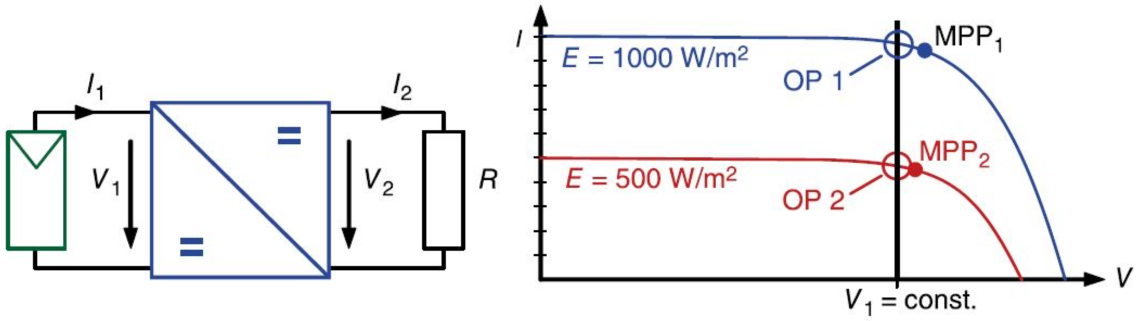


Figure 26.- Installation with DC/DC converter. Source: Mertens (2018)

2.2.1.3 DC/AC Inverter

This device helps to convert the direct current (DC) output of a photovoltaic panel into Alternating Current (AC). They can be used both in isolated *stand alone* installations with AC loads and in huge photovoltaic power systems with grid connection. The power of the panels depends on the working point as it was previously mentioned. With the aim to maximise the energy production the generator must adapt to the load, so that the working point always matches the maximum power point M_{pp} (*Maximum Power Point Tracking*). The modern inverters incorporate the tracking function to follow up the maximum power point. Depending on the type of installation, isolated or grid-connected, the inverter performance will differ. In both cases the energy output of the photovoltaic panels must be optimised and maximised:

- **In isolated *stand alone* power systems** the inverters must provide a voltage in the AC side as constant as possible so that the loads are not subjectd to voltage variations.
- **In *grid-connected* (or *grid-tied*) power systems** the inverters must produce a voltage as similar to the grid voltage as possible (voltage level and phase synchronism).

Depending on the number of inverters the power systems are classified into:

- **Installations with one only inverter:** Normally used in small power systems. Main advantages are the reduced initial investment and maintenance costs. The disadvantage is that the whole system depends on one inverter and therefore, one fault will produce its collapse (Figure 27).
- **Installations with several inverters:** In big and medium size installations each chain can connect to its own working point and function according to its working point. In big installations several arrays are connected in parallel to the inverter (Figure 28).

2.2.1.4 Measurement of the energy generated

The grid-connected PV systems must have a meter that controls the amount of energy that is generated and the energy that is sent to the grid. There are two types of installation depending on the directionality of the meter:

1. **Unidirectional Meter:** a specific meter for the PV generation and another meter to measure the energy consumed by the installation are employed. In this way all the energy generated is fed into the grid. This situation is produced when it is not economically profitable to consume due to the high cost of the premiums for the renewable energies (Figure 29)
2. **Bidirectional Meter:** this meter measures both the energy fed and the energy taken from the grid separatedly. Because of the decrease to the premiums to self-consumption, this has become economically advantageous, thus gaining support against the grid connection. If the solar energy that has been generated must be known, a meter should connected between the photovoltaic installation and the bidirectional meter, as shown in Figure 30.

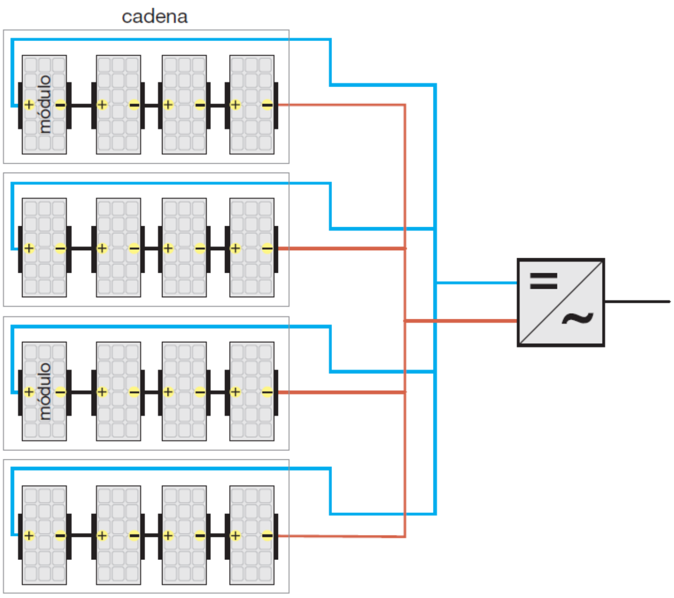


Figure 27.- Installation with one inverter. Source: ABB (2011)

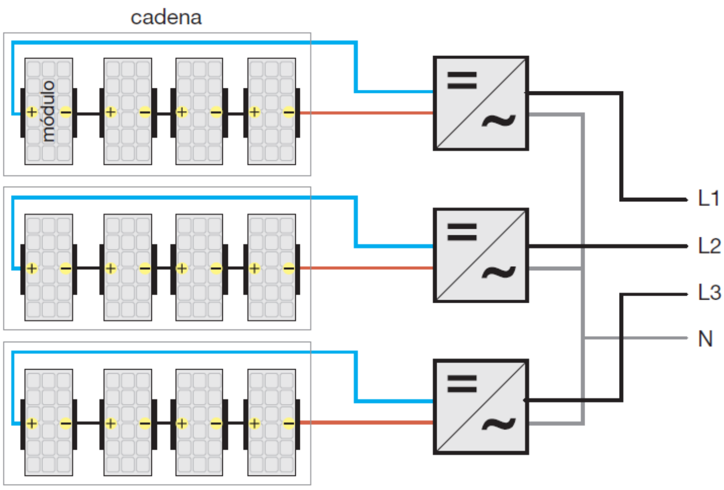


Figure 28.- Installation with several inverters. Source: ABB (2011)

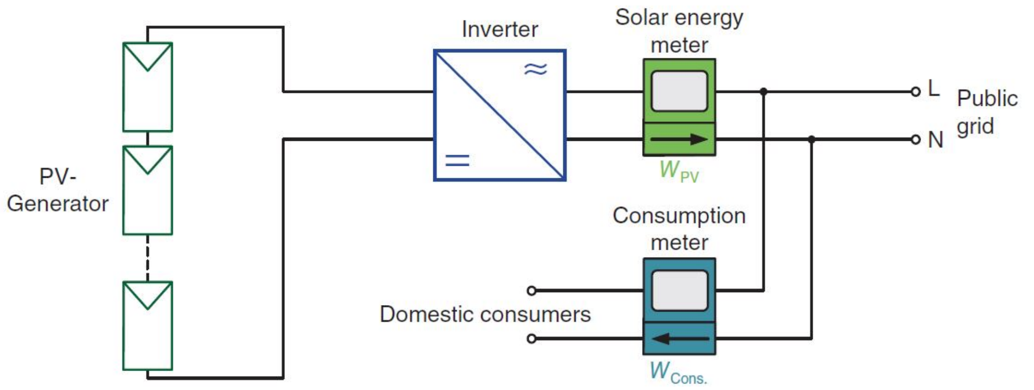


Figure 29.- Installation with unidirectional meter Source: Mertens (2014)

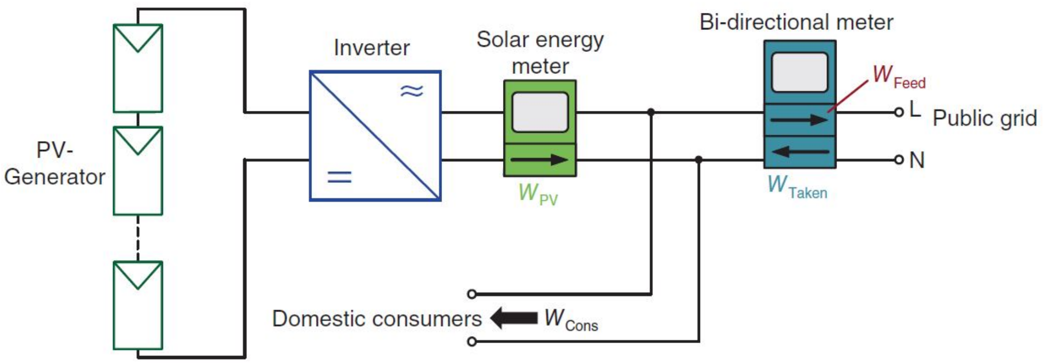


Figure 30.- Installation with bidirectional meter. Source: Mertens (2014)

2.2.1.5 Energy storage

In general, the storage of the energy produced by the PV systems is carried out by batteries. The batteries are one of the most important elements in installations isolated from the grid because they help to feed the loads in the absence of solar radiation. There are different technologies of batteries available in the market such as lead, nickel, lithium-ion, lithium polymer, etc. However, in autonomous PV systems the lead is used almost exclusively due to its reduced cost, although the other systems present advantages such as a high density storage or a lower self-discharge. Having a lower cost is an essential factor because the average life of the batteries is lower than 10 years and they make up a great part of the total cost of the power system. It is very important to know the charge and discharge cycles to which a battery may be subjected, because these deteriorate its capacity. Capacity is defined as the maximum energy that can be stored in the battery and that can be extracted from it as electrical energy. The deterioration of the capacity increases when the discharges are deeper, so it will be necessary to have a charge controller to avoid shortenings in the useful life of the battery (taking useful life as the period in which the battery capacity falls below 80% of its nominal capacity). In Figure 31 the useful life of the main technologies of lead batteries is represented in relation to the depth of discharge.

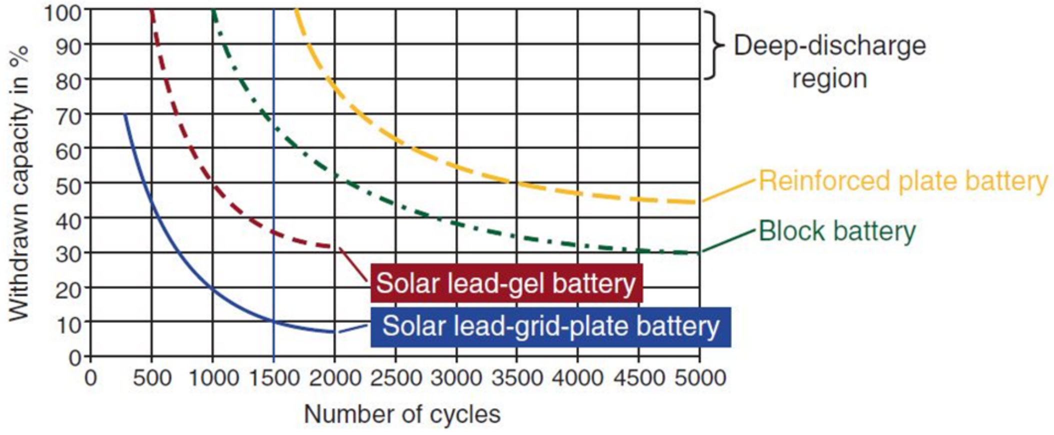


Figure 31.- Useful life of batteries in relation to depth of discharge. Source: Mertens (2014)

Solar lead-grid-plate battery: These are modified starting batteries. The battery terminals thicken and lead plates harden with antimony. They only reach a useful life of 300 charge cycles if the depth of discharge is of 70% and 1000 cycles if the depth is of 20%.

Solar lead-gel battery: In these batteries, the electrolyte thickens with additives until it becomes a gel. This type of batteries may be fully sealed (unlike the liquid electrolyte type). The useful life of the technology is approximately the double of the conventional lead batteries.

Reinforced plate battery: The useful life of these batteries is very high, about 15-20 years. Normally, they are used for emergency systems and their cost is 2 to 3 times higher than conventional batteries. They can stand up to 3500 charge cycles for discharges of 50%.

Block battery: Unlike the previous one the electrodes are surrounded by a common protecting cover (not individual), so they are cheaper. They can stand up to 2000 charge cycles for discharges of 50%.

2.2.1.6 Charge controller

Similarly to batteries, the charge controller is a fundamental element in isolated *stand-alone systems*. This element is in charge of controlling the state of charge of the batteries. As it has been said in the previous section, batteries need care in their use in order to extend their useful life. The main tasks of the charge controller are (Figure 32):

- Protection against overcharge.
- Protection against deep discharges.
- Prevention of undesired discharges.
- Monitorisation of the charge state.
- Adaptation of the battery technology (electrolyte/gel).
- Voltage conversion (an inverter is connected to the regulator output).
- Follow up of MPP.

Figure 32.- Charge regulator Steca PR 0505. Source: Steca

2.2.2 TYPOLOGY OF PV SYSTEMS

2.2.2.1 Isolated power systems (off-grid)

This type of systems unconnected to the grid are formed mainly by PV panels (1) working as generators and a management and storage system (2,3,4,6) that guarantees the energy supply under low illumination conditions or darkness. This type of configuration represents a huge technical and economic advantage when there is not grid available near the place. This type of PV systems is sketched in Figure 33. DC wiring is shown in blue while AC wiring appears in red. The DC generated by the PV panels is distributed in the distribution board in the DC side. Protection devices against overcharges, overvoltages, short circuits are found in these boards too. The management of the DC is carried out by means of the charge controller, which is connected to: the DC loads (also connected to the batteries), the storage systems (batteries) and DC/AC converter. The converter will transform the DC into AC to eventually feed the AC loads.

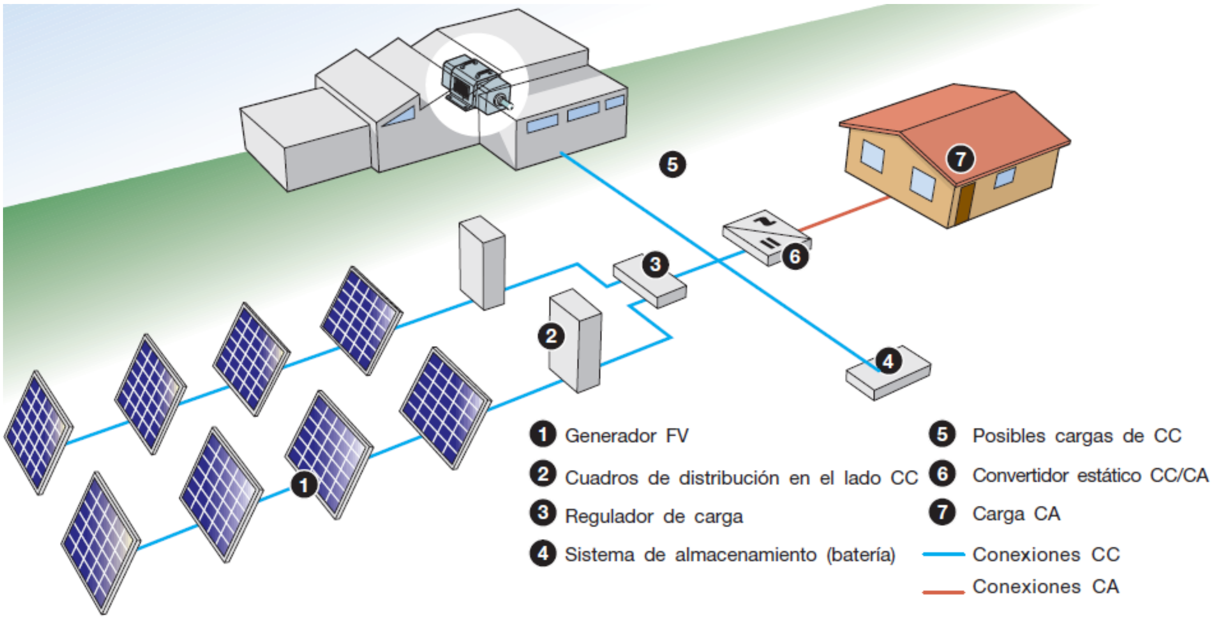


Figure 33.- Isolated stand-alone system. Source: ABB (2011)

2.2.2.2 Grid-connected photovoltaic (PV) systems

There are two main types of grid-connected PV systems: big solar farms and installations with small and medium power capacity. The latter takes the energy from the grid when the PV panels (1) cannot produce enough energy. When the PV production exceeds, the excess is injected to the grid, thus working as big accumulator. As a consequence, these systems do not need storage systems (Figure 34).

One of the advantages of the grid-connected systems is the distributed generation. Production near the consumption centres is more valuable than the production in big traditional power systems because the transmission losses and the maintenance costs are reduced. On the other hand, production during high solar radiation periods (during day time) helps to reduce the requirements of the grid when the demand gets higher.

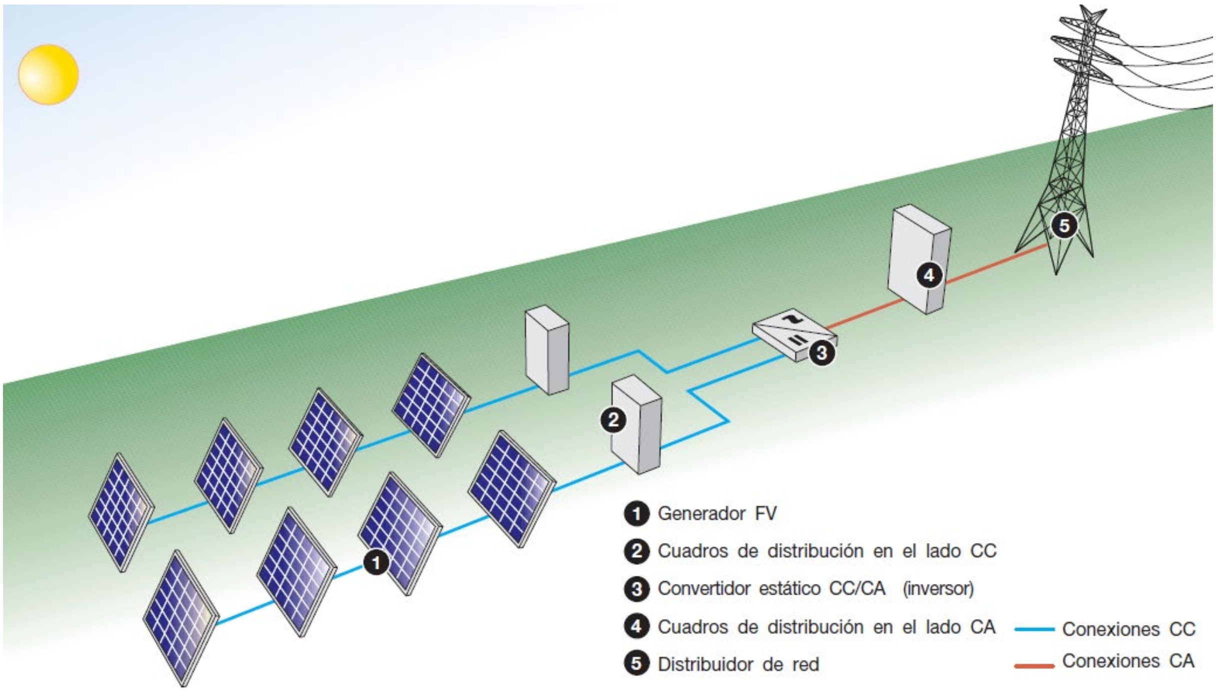


Figure 34.- Grid-connected system. Source: ABB (2011)

2.2.3 POTENTIAL LOCATIONS

The locations for PV systems along the road asset are later discussed in chapter 5 and chapter 6. However, the following possible locations were found by simple surveying the technical literature: on the cut slope of the road, over/on the noise barriers, integrated into the road surface (solar road), as solar canopies in parking lots, aside the road, in rest or service areas and over traffic signs, lampposts or traffic lights. Out of these potential locations, one of the most popular in Europe in the last 10-20 years have been the PV noise barriers, in which PV solar panels are placed over the solar barrier or integrated into them. In Figure 35, the most typical PVNB typologies are shown.

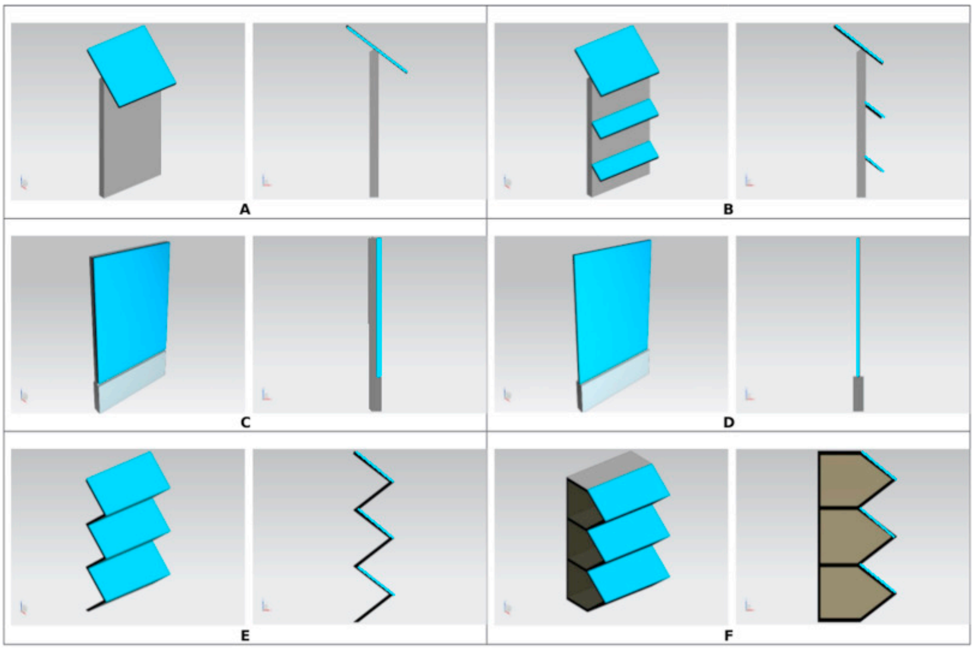


Figure 35.- Different typologies of PVNBs. Source: Wadhawana and Pearce (2017)

PVNBs are primarily noise barriers with the added functionality of generating electricity, and therefore it is crucial to ensure that the required noise attenuation is properly accomplished. Although only very few short references have been found on the ability by PVNBs to mitigate the noise from the traffic, research results suggest that they are able to generate a quiet zone (noise shadow), similar to that of a conventional noise barrier of similar height. Consequently, PVNBs can be designed to produce renewable energy while properly fulfilling their primary function. There exist three ways this can obtained (for experiences so far, see in chapter 5) :

- By using noise retention modules (as in the PVNB in Uden, The Netherlands). In this case, the glass is used for blocking the noise and as an encapsulant for the solar PV cells.
- By placing PV panels over conventional noise barriers (as in the PVNB in Tullamarine, Australia). Most of the (old) PV noise barriers belong to this group.
- By completing the PV modules with extra element to fulfill the noise blocking properties (as in the case of Freising, Germany, where extra ceramic plates were placed to gain the required weight).

Thus, sometimes the size of the PVNBs must be slightly adapted (they must be larger or heavier than the ideal design) to maintain the noise blocking function and resist high wind loads.

In general, the way and degree to which PVNBs mitigate the noise from traffic relies on the proportion of the glass (where solar cells are encapsulated) to the other materials (if any) existing in the barrier. As the glass surface of a PV module can only reflect the sound, when (if) sound absorption is required, a cassette or zigzag design has to be used (see Figure 35) so that the combination of glass (sound reflector) and other absorptive material makes it possible.

Studies performed have revealed that a PNVB might result in a slight increase in noise on the side of the road opposite the PV panel. However, that increase would be minimal, unlikely to be noticed by residents, and potentially minimized by carefully positioning the PV modules or using certain vegetation behing the barrier. Other research indicates that the careful positioning of the PV can mitigate reflection issues.

2.2.4 CLEANING AND MAINTENANCE

2.2.4.1 Cleaning and maintenance of PV panels

Panel cleaning is a factor to take very much into account because noticeable decreases in the installation performance may be produced due to dust, bird droppings, sand, tree leaves, etc., that reduce the area available to collect the solar radiation. According to a review on air pollution and soiling implications for PV generation carried out by researchers of the Renewable Energy Research Group (RERG) of The Hong Kong Polytechnic University (Song, Liu and Yang, 2021), air pollution and soiling of PV panels can greatly affect the energy generation with reductions of PV capacity factors of 2%-68% and 1%-50%, respectively, and cause important economic losses in regions with large solar resources. It was also found out in this study that location is a critical factor, with more losses in PV generation due to air pollution and soiling in the Middle East than in other regions.

As for the mechanisms of energy generation reduction, air pollution mostly reflects, scatters and absorbs the solar radiation potentially reaching the PV surface, while soiling reduces the transmittance by covering the PV panels. In this sense, the study concludes that manual cleaning and mechanical cleaning are the most effective strategies to remove the soiling from PV panels, although the costs are high. It should be noted that the angle formed by the panels in the more specific PVNBs together with frequent rain events in certain locations can be of help for improving the efficiency of the natural cleaning (see section 5.2).

Apart from the poorer performance, hot-spots may be produced. This problem may cause the breakdown or faulty operation of the whole PV panel due to the total or partial concealment of a cell or small group of cells. In Figure 36, the effect that dirt has in the I-V curve of a PV cell for an irradiance of 310 W/m^2 is shown. According to the results, performance was reduced by talcum powder (9-31%), dust (60-70%) and sand (70-80%). Therefore, a regular clean up is essential to keep performance constant, avoid sharp falls and also prevent hot-spots.

Regarding the maintenance of the PV panels, main actions to carry out are the following:

- Checkup of tightness of the panels junction boxes.
- Checkup of electrical connection with external DC bus.
- Measurement of open-circuit voltage Voc.
- Measurement of short-circuit current Isc.
- Panels will be regularly cleaned to avoid poor performance due to dust and/or dirt.

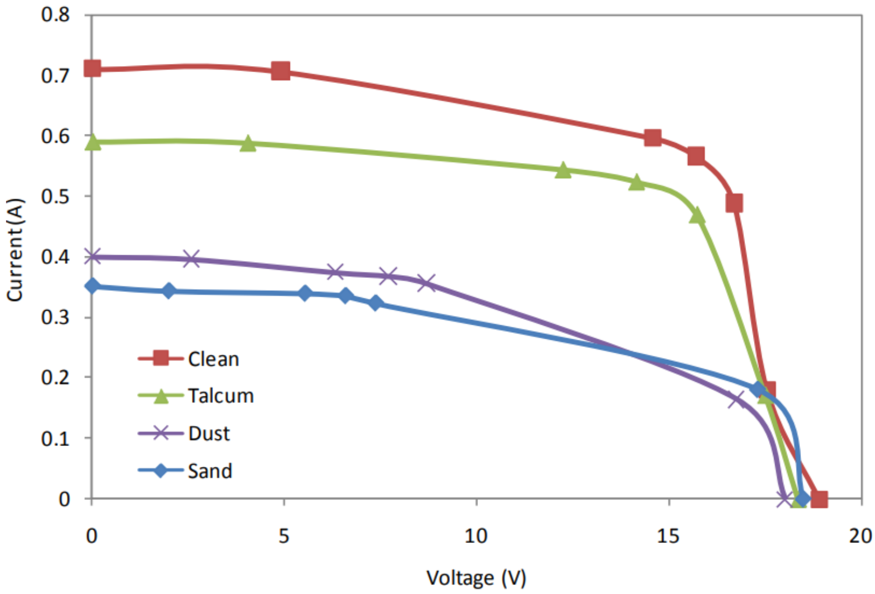


Figure 36.- Influence of dirt in I-V curve I-V for different materials. Source: Sulaiman et al. (2014)

2.2.4.2 Checkup of the structure and support of the panels

The structure that supports the panels is normally made of aluminium, with bolts being of stainless steel. Therefore, they they do not require anti-corrosion maintenance. Main tasks to carry out are:

- Checkup of the possible deformations, cracks, etc., produced by the wind.
- Checkup of the state of attachment of panels to the structure, verifying bolts torque.
- Checkup of tightness of the panel case, verifying mainly that the joints are fully sealed.
- Checkup of PV ground connection. Periodical measurements of ground resistance value.

2.2.4.3 Check up of the Inverter

- Reading of data registered and of the errors memory (in order to identify any undetected error).
- Clean up of heat sink and replacement of the air filters. Checkup of right functioning of fans.
- Inspection of dust, dirt, humidity and water leaks in the distribution board.
- Revision of electrical connections. In case of loose connections they must be tightened.
- Checkup of connections Temp by IR thermography. If any connection surpasses 60 °C, V and I will be measured to verify if they are within nominal values. If not, the connection will be replaced.
- Visual inspection for fuses and existing disconnectors.
- Testing of protection elements: differential, magnetothermic and power switches.
- Revision of the control voltage devices 230 V AC and auxiliary 24 V DC.

2.3 MINI-HYDRO ENERGY

The hydro energy here reported strictly corresponds to mini hydro energy (i.e. power capacity lower than 10MW) harnessed from rivers and dams in areas close to the road asset. The hydroelectric power plants transform the hydraulic mechanical energy into electrical energy by taking advantage of the difference between levels. The energy is first transformed into mechanical rotating energy in the turbine, and then into electrical energy thanks to the mechanical coupling between the turbine and the electric generator. The hydro energy is one of the most mature and consolidated energies among the renewable energies. Main references used for the development of this section are: Agüera (2002); Gulliver and Arndt (1991); IDAE (2006); IDAE (2014); IHA (2021); SHR (2012); and UNIDO (2020).

According to REN21 in their report of the global situation of the renewable energies in 2020, the hydraulic energy concentrates 45% of the renewable production at world level with a total of 1150 GW of installed power, followed by wind energy and photovoltaic energy with 651 and 627 GW, respectively (Figure 37). In Europe, according to the International Hydropower Association, Norway is the first producer with 32 GW while Spain is in fifth position with 20 GW (Figure 38). As for the Small Hydro energy, in 2010 nearly 21800 plants were in operation in the EU, with a total installed capacity of ≈13 GW. It was expected that in 2020 the number of plants would reach up to 24000, with a total capacity of ≈17 GW (SHR, 2012).

POWER		2018	2019
Renewable power capacity (including hydropower)	GW	2,387	**2,588**
Renewable power capacity (not including hydropower)	GW	1,252	**1,437**
Hydropower capacity[2]	GW	1,135	**1,150**
Wind power capacity	GW	591	**651**
Solar PV capacity[3]	GW	512	**627**
Bio-power capacity	GW	131	**139**
Geothermal power capacity	GW	13.2	**13.9**
Concentrating solar thermal power (CSP) capacity	GW	5.6	**6.2**
Ocean power capacity	GW	0.5	**0.5**

Figure 37.- Global renewable power installed at the end of 2019. Source: REN21 (2020)

Rank	Country	Total installed capacity (MW)
1	Norway	32,671
2	Turkey	28,503
3	France	25,557
4	Italy	22,593
5	Spain	20,414
6	Switzerland	16,863
7	Sweden	16,478
8	Austria	14,545
9	Germany	11,022
10	Portugal	7,193

Figure 38.- European countries with highest hydro power in 2020. Source: IHA (2020)

2.3.1 CLASSIFICATION (SMALL TO PICO POWER PLANTS)

The United Nations Industrial Development Organisation (UNIDO), designates **mini hydro** to the hydro power plants with power under 10 MW. Depending on their power installed they can be classified in small, mini, micro or pico power plants (Table 4).

Table 4.- Classification of mini hydro power stations depending on the power installed.

Designation	Power installed (kW)
Small stations	10000 – 1000
Mini stations	1000 - 100
Micro stations	100 - 5
Pico stations	< 5

2.3.2 TYPE OF MINI-HYDRO POWER PLANTS

Mini hydro power plants are very conditioned by the topography and hydrography of the area, which are going to influence the civil works and the selection of the type of plant. The main types of mini plants are:

- Run-of-river hydro plants
- Hydropower plants at the foot of dam
- Hydro power plants in irrigation canals or water transfers

2.3.2.1 Run-of-river hydroelectric power plants

In these plants, part of the water is diverted through pipes, tunnel leadings or canals and led to the plant where it will be turbined. Once turbined it will be sent back to the river. All the run-of-river plants are characterised by directly depending on the hydrology of the place, because they do not have regulation capacity (storage) and therefore, their production depends on the river flow. In some plants, little dams are built in the water intake to facilitate the entrance of water to the canal or the diverting pipe but these dams do not have regulating function. The water diverted is led up to the storage chamber, from where the water passes through the penstock to be turbined in the lowest point of the plant. Once turbined the water is discharged into the river flow through the drainage canal or discharge canal.

2.3.2.2 Mini hydro power plants at the foot of dams

The use of mini hydro power stations at foot of dam is possible when dams can be built in the river flow to regulate and store the flow variations. This is the most important difference respect to the run-of-river plants. Other differences are the storage and regulation capacities. Thanks to these characteristics, these plants can control their production volume and increase it during peak hours of consumption. Under the intake there is the so called “dead zone”, which simply stores water not useful to be turbined. Depending on the capacity over the intake (total amount of water that can be turbined), there can be hourly, daily or weekly regulation. Due to the small size of the mini hydro power plants, the regulation is usually on a daily basis. Among this group of plants those aimed at other uses, such as irrigation or water supply for towns are also included.

2.3.2.3 Hydro power plants in irrigation canals or water transfers

There are mainly two models to introduce a hydro-electric power station in an irrigation canal or in canals aimed at water transfer:

- **Model A: Widening of the canal to install the water intake, the power plant and the diverting canal.** To ensure the water supply for the transfer or irrigation, an alternative canal must be built for situations of turbine stops. This solution must be foreseen when designing the canal or taking advantage of an important remodelling.
- **Model B: Canal with duckbill spillway.** If the canal is already built the water intake is performed by a duckbill spillway to reduce width and facilitate its implementation. From the intake, the water is led to the turbine by the penstock in parallel to the canal. Once turbined the water is discharged into the main canal by the restitution canal.

2.3.3 MAIN COMPONENTS OF THE MINI HYDRO

2.3.3.1 Hydraulic turbines

Hydraulic turbines are the key elements of a hydro power plant. They make use of the mechanical energy of the water (kinetic and potential) by transforming it into rotating energy and transferring this movement by means of a shaft coupled to a generator that eventually produce the power. The hydraulic turbines can be classified into two main groups: action turbines and reaction turbines.

Action turbines

The water flow pressure becomes kinetic energy. The action turbines make use of the flow speed to make them rotate so that all the energy is transmitted to the turbine impeller in the form of potential energy. Among this group the following stand out (Figure 39):

- **Pelton wheel**: This type of turbine is designed for high heads (high pressure) and low water flows. It is composed of a runner (circular disk) with buckets. The water flow enters in the turbine led and regulated by one or several nozzles, falling upon the blades and causing the turning motion of the turbine. In general, these turbines have high availability, low maintenance cost and a quite high performance, reaching 90% for design conditions.
- **Ossberger turbine or cross-flow turbine:** These turbines shares several characteristics with the Pelton wheel. They are composed by a rectangular cross-section nozzle and cylindrical impeller. A longitudinal blade guides and regulates the flow entering the turbine. This type of turbines have a very extended scope of application because they can be installed in plants with heads among 1

and 200 metres and with a range of flow variation quite high. Its performance is limited to 1 MW, what makes them suitable for mini hydro power plants. Their performance is lower than that of the Pelton turbines, reaching 85% for design conditions.

- **Turgo turbine:** This type of turbines are constructive modifications of the Pelton turbines. In these turbines, the runner is cheaper to build than in the Pelton turbines and of smaller diameter for the same flow. They operate in a head range that overlaps with those of the Francis and Pelton turbines. There are big installations with this type of turbines, but they are normally used in mini hydro power stations where the low cost is a priority.

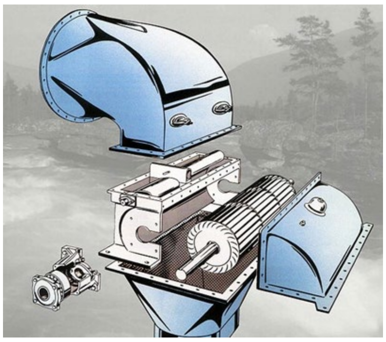
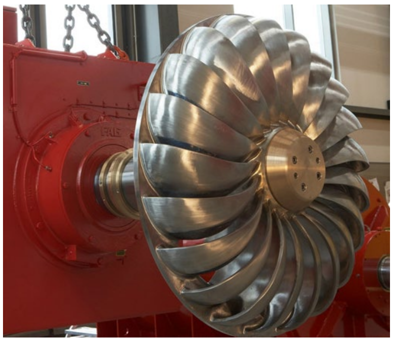




Figure 39.- Pelton wheel, Oossberger turbine and Turgo turbine.

Reaction turbines

In this turbines the water pressure works as a force on the blades surface that decreases as it advances on its way out, so that at the rotor exit the water flow usually has a pressure below the atmospheric. Among this group the following stand out (Figure 40):

- **Francis turbines:** The main characteristic of this turbine is its capacity to adapt to all types of flow and heads. They take in the flow with radial direction and as it passes through the turbine the flow becomes axial. This type of turbines can reach performances above 90% in design conditions and allows flow variations between 40% and 105% of the design flow and variations of net head between 60% and 125%. These characteristics have made them the most widely used turbine both in small and big hydraulic.

- **Kaplan turbines and propeller turbines:** The plants with this type of turbines are composed by an inlet chamber, a flow guide-vane (which may be fixed or not) and a runner formed by 4 or 5 blades in ship propeller shape. The blades of these propellers have orientation capacity what helps them to optimise the performance for flow variations. They have a performance close to 90% for design conditions and a capacity of flow variation from 15% to 110%. The implementation of this type of turbines usually includes a vertical axis and is generally used for conditions of big variable flows and with small net heads.

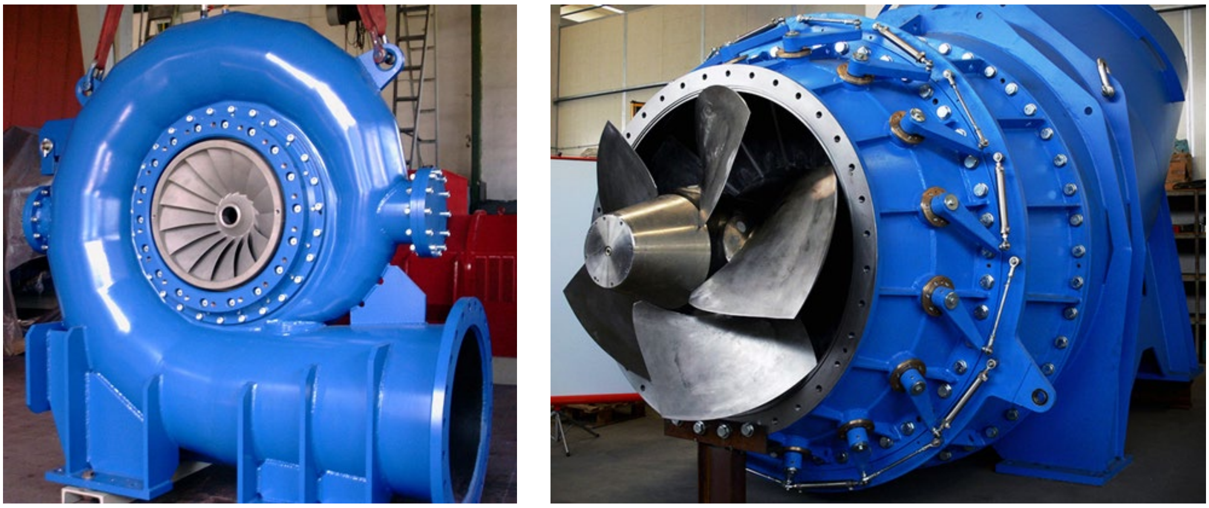


Figure 40.- Francis and Kaplan turbines.

Range of use of mini hydro turbines

The scope of use of a hydraulic turbine will be mainly determined by the head H (m) and the flow Q (m^3/s). In general, the application of the turbine would be:

- **Pelton**: big heads, independently from the flow variation.
- **Kaplan**: small heads and variable flows.
- **Francis**: big heads, independently from flow variation.

For a suited decision, turbine manufacturers usually elaborate abacus like the one in Figure 41. With these grahps, it is possible to select a turbine depending on the nominal flow Q and the net head H, and obtain the electrical power generated with that turbine.

This abacus is mainly focused on mini hydro as the range of power of the turbines on it goes from 5 to 10000 kW. The electric power P (W) generated can be determined with the following equation:

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta_T \cdot \eta_G$$

Where:

- ρ: water density, 1000 kg/m^3.
- g: terrestrial gravity, 9.81 m/s^2.
- Q: design flow, m^3/s.
- H: net head, m.
- η_T: turbine performance for the design values of H and Q.
- η_G: nominal performance of the generator.

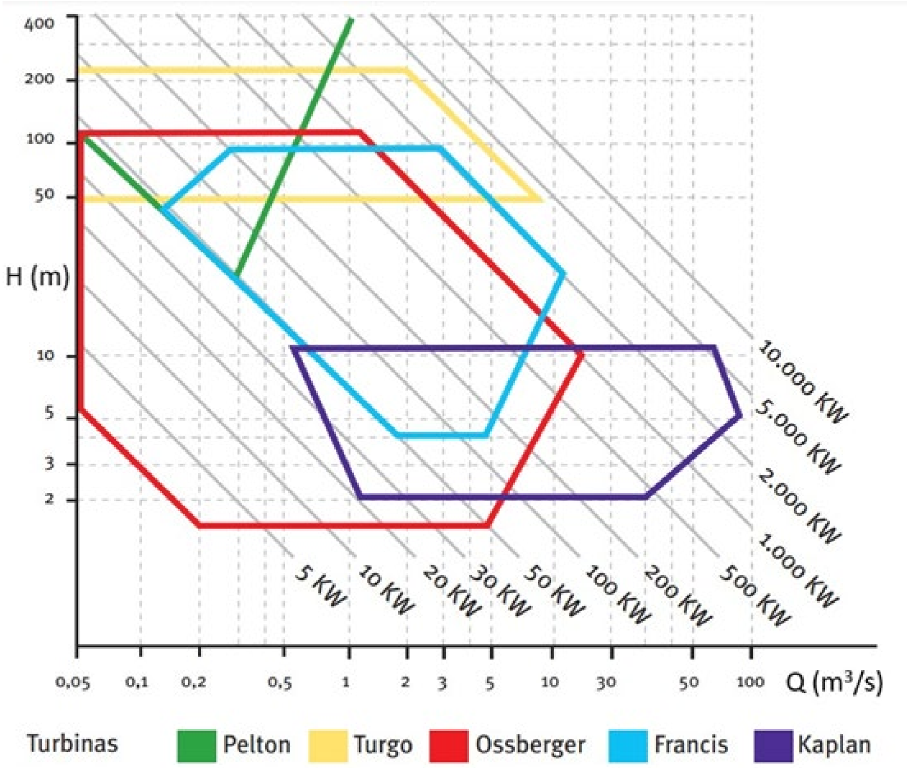


Figure 41.- Range of use for different (mini) hydro turbines. Source: IDEA (2006)

2.3.3.2 Weirs and dams

Weirs and dams are built to cause retentions in river courses with the aim to increase the net head and provide capacity of flow regulation (Figure 42). They mainly differ on their height, the dam being a higher construction less used in small hydro. They are both used mainly in foot of dam and in run-of-river plants.

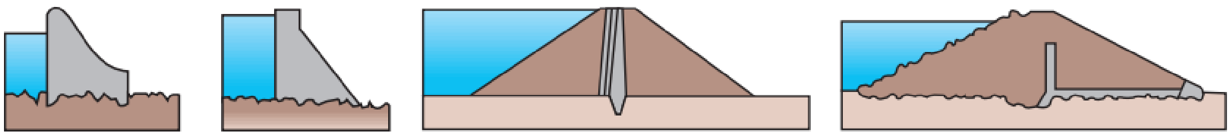


Figure 42.- Concrete, riprap and earth weirs. Source: IDAE (2006)

2.3.3.3 Spillways and floodgates.

These elements help the spill of big flows in floods to avoid structural damages in the dams or weirs. All the types of plants include them. The big difference between both elements are the mobile parts with which the gate is equipped that let or not the pass of the flow or its regulation.

2.3.3.4 Water intake

They are mainly used in run-of-river and irrigation canal plants. They consist of a structure whose aim is to divert the river flow and facilitate its pass from the weir or dam. The intake normally has a grating that avoids the solid bodies from entering the canal and a safety gate that is called bulkhead gate. In normal functioning this gate stays open, closing only in case of emergency or when an inspection or repair is going to be carried out. There is another type of intake, the submerged intake. In this case, a transverse canal is excavated in the river course, so that the water enters through the upper grating that protects this inlet, and goes out crossing across the river course to get into the diverting canal (Figure 43).

Figure 43.- Water intake with grating. Source: IDAE (2014)

2.3.3.5 Penstock

This is a pipe in charge of taking water to the turbine. These pipes are built with high-resistance materials as they must bear huge pressure variations because of water hammers and huge temperature differences. The diameter is normally defined in relation to the flow, and depending on the topography of the place the pipe could be buried or not. In case of not being buried, the pipe will be fixed by anchors that include expansion joints to absorb overpressures and volumetric expansions due to temperature variations. In case of buried pipes, a sand bed is normally placed at the end of the trench, right below the pipe. The pipe will experiment less temperature variations but it may suffer from corrosion problems depending on the type of soil.

2.3.3.6 Forebay

The forebay is a storage structure placed at the end of the canal where the penstock starts towards the central. Its main function is the dissipation of the energy in the water before it reaches the turbine, but it has a small regulation capacity too. All the types of mini hydro power plants include them, although their size depends on the type of plant. When designing the forebay geometry, the energy losses and whirpools must be carefully avoided, both upstream and in the forebay. If the penstock is not sufficiently submerged, a flow like this can cause the formation of vortices that drag air into the turbine, thus generating cavitation and therefore, decreasing the performance of the mini station.

2.3.3.7 Power house

The location of this building must be analysed considering the accessibility and the topographic, geological and geotechnical studies. Its location can be quite varied: next to the weir or foot of dam, buried or placed downstream to increase the head. Independently from the building location, this must have the necessary conduction elements for the water to reach the turbine with the lowest possible energy losses and the canalisations for the drainage towards the discharge canal (Figure 44).

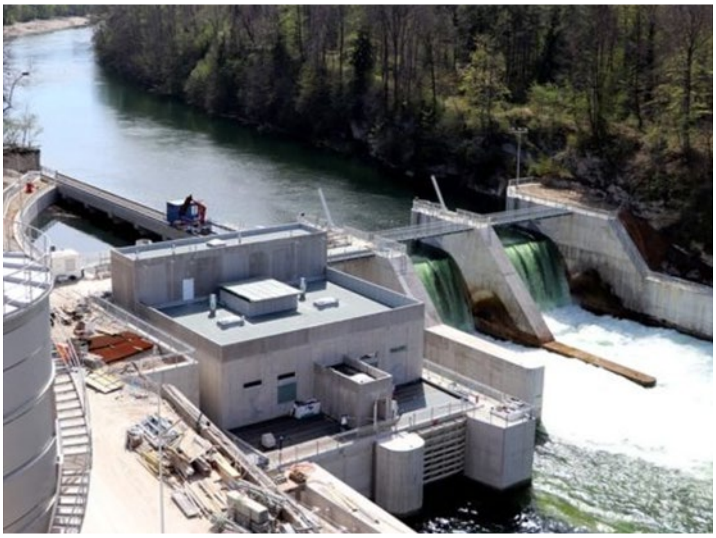


Figure 44.- Power house of a mini hydro power plant. Source: ambientum.com

The power house will include the valves and gates required to regulate and even stop the flow during the possible stops for failures or maintenance. In the building the electrical machine for the energy generation (syncronous or asyncronous machine) will be found along with the power transformer for increasing the voltage for the transportation of the energy as well as the electrical protections.

2.3.4 CLEANING AND MAINTENANCE

To assess the payback profitability of a mini hydro plant not only its location, design and construction must be taken into account, but also the failures in the components originated by wear or misuse. In order to mitigate this problem, maintenance strategies must be designed that increase the availability of the turbine. To know the different failures in the components is key to develop right maintenance strategies.

In Figure 45, the incidence rate associated to each of the electrical systems of the hydro plant is shown. According to the graph, 44% of the incidences are in the electrical and hydraulic protections, followed by the incidences in the turbine. To carry out the maintenance strategies the different types of maintenance used in the industry (corrective, preventive and predictive) have to be applied, whose planning will reduce the frequency of faults, operation costs and stops for repairs. The main maintenance tasks are:

- Control of proper functioning of gates.
- Painting of gates with anti-corrosion paint.

- Total cleanup of the canal.
- Cleanup of the water inlet grating, getting rid of leaves, branches, floating litter, etc.
- Cleanup of forebay.
- Inspection of turbine chamber, admission valve and pipes, searching for wear or leaks.
- Inspection of the seals looking for leaks in the plain bearings of the turbine blades.
- Lubrication of plain and roller bearings.
- Inspection of seals looking for leaks in: plain bearings of the guide vanes (Francis), plain bearings of the turbine (Pelton), shaft and plain bearing of the generator.
- Periodical analysis of vibration in turbines.
- Revision of bolted joints and torque of the elements of the turbine and the supporting structure.
- Revision of the proper position and orientation of the turbine buckets.

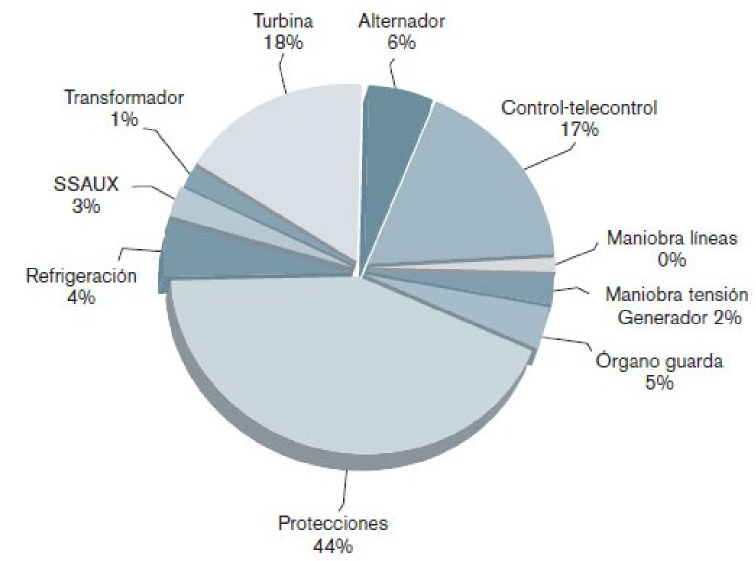


Figure 45.- Incidence rate of the electrical systems of the hydro power. Source: tecnicaindustrial.es

2.4 MICRO-SCALE BIOMASS POWER PLANTS

Bioenergy is derived from a wide range of organic wastes such as those coming from the agriculture (crop residues, animal waste, etc.), the forestry (logging residues, wood processing by-products, etc.), and other types of biological waste (food waste, municipal waste, etc.). In 2016, forestry accounted for more than 61% of all the biomass for energy purposes in the EU, with 27% coming from the agriculture and 12% from municipal and industrial waste (Scarlat et al., 2019).

Biomass is used for providing heating, power generation and combined heat and power (CHP) and is one of the most important source of renewable energy in the EU along with the wind and solar power. As for the end use, in 2016 heating accounted for the 75% of the bioenergy consumed, electricity for the 13% and biofuels for the remaining 12%, approximately. In that same year, Germany, UK, Italy, Finland and

Sweden were the largest bioelectricity consumers in the EU (Scarlat et al., 2019). Bioenergy is also of great importance in the US, accounting for 45% of the total renewable energy produced in that country, where renewable sources represent approximately 11% of total energy (BPA, 2021). In 2019, biomass provided about 5% of total primary energy use in the US (EIA, 2020).

Biomass power plants use natural materials such as forestry, agricultural or municipal waste to generate clean, renewable electricity. For this, the organic materials are burned to produce steam that either runs a turbine to generate the electricity, or provides heat for industrial and/or domestic purposes. Compared to other renewables energies, bioelectricity is a reliable energy source, meaning that it is available when required (24/7) as not being affected by the weather.

Several methods exist nowadays to convert biomass into electricity, the most common of which is direct combustion of the waste material. Other options include the gasification, which produces a synthesis gas with usable energy content by heating the biomass with less oxygen than needed for total combustion; pyrolysis, which produces bio-oil by rapidly heating the biomass in the absence of oxygen; or anaerobic digestion, which produces a renewable natural gas when organic matter is decomposed by bacteria in the absence of oxygen. As said before, most biomass power plants directly burn the organic waste to produce steam, which drives a turbine that spins to run a generator that eventually generates the electricity. When the steam is also employed for industrial of domestic heating purposes, the plants are called Combined Heat and Power plants (CHP). The following are the main elements existing in a direct-use biomass power plant (WBDG, 2016):

- Fuel storage and handling equipment
- Furnace
- Boiler
- Pumps
- Fans
- Steam turbine
- Generator
- Condenser
- Cooling tower
- Exhaust / emissions controls
- System controls (automated).

The schematic process of a direct-use biomass power plant with steam turbine is shown in Figure 46. Apart from the steam generation elements, other elements are key for the proper bioelectrity generation such a the fuel storage, fuel handling equipment, short-term storage for biomass, an automated control system and other manual equipment like loaders or cranes for handling the materials, all of this meaning relevant costs in labor and equipment operations and maintenance (O&M). Figure 47 shows a diagram including the complete process for the bioelectrity generation in a large-scale biomass power plant.

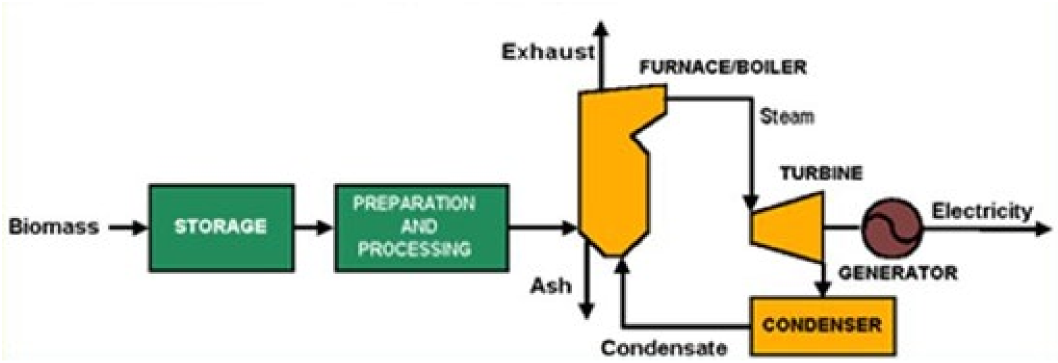


Figure 46.- Schematic process of biomass power plants. Source: WBDG, 2016.

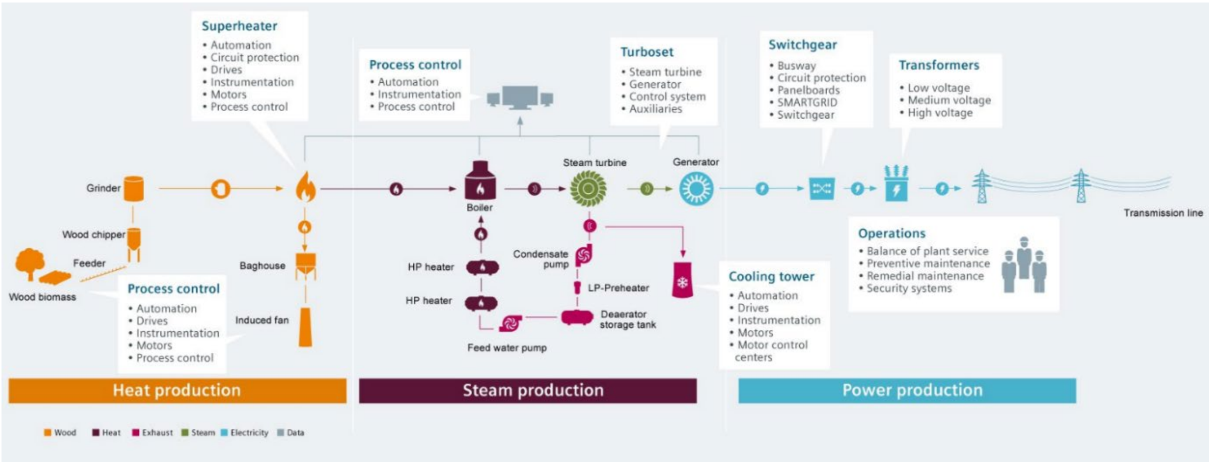


Figure 47.- Components of a large-scale biomass power plants. Source: Siemens (2021)

Large-scale biomass power plants in the range of 5 to 25 MW generates electrity at a cost between 3000 and 5000 $/kW of electricity. In terms of Levelized Cost of Energy ($/kWh), this means between 0.08 and 0.15 $/kWh, although this could greatly increase with fuel costs (WBDG, 2016).

For NRAs, the generation of electricity from large, medium or even small-scale power plants is obviously not an option, at least not a natural one. On the other hand, the use of micro-sized combined heat and power production (micro-CHP) units could potentially be a solution in the medium term.

According to Dong et al. (2009), micro-Scale CHP are small-scale CHP systems with electricity output lower than 15 kW. These systems are particularly suitable for applications in large buildings like office buildings, commercial buildings, hospitals, schools, etc. In addition, as the micro-scale units can work off the grid, they provide a higher degree of reliability to the power grid and keep the local system running during major grid failures like blackouts.

Currently, large and medium-scale biomass CHP power plants are successfully commercialized in several

European countries, and micro-scale and small-scale CHP systems are undergoing rapid development and very shyly emerging on the market.

In terms of technical development, there exist several conversion technologies that can be implemented in micro biomass CHP plants: gasification, pyrolysis, etc., for the primary conversion (the one that converts biomass into steam, gas, water or liquid products); and steam turbine, gas tubine, Stirling engine, etc., for the secondary conversion (the on that converts the products from the primary conversion into heat and power). Among all these conversion technologies, the Stirling engine was considered a very promising one for its high effiency, but its relatively high cost somewhat limited its market expansion. On the other hand, there seems to be a growing interest in the direct-use (primary conversion) and the Organic Rankine Cycle (second conversion) for the development of small-scale biomass CHP plants due to their lower and similar cost as compared to Stirling engines and traditional Rankine Cycle, respectively (Mascuch et al., 2020).

In addition to the lower costs, the organic fluid used by the ORC systems as working fluid makes them run at lower temperatures and pressures than systems using the conventional steam process. These aspects, together with their low mainantenace and autonomous operation, make the OCR systems a very suitable solution for micro biomass CHP plants (Obi, 2015; Mascuch et al., 2020).

According to different authors in Dong et al. (2009), the typical electrical efficiencies for CHP plants under 30 kW are 6-8%, while ORC-based systems are able to generate with efficiencies of up to 15%. The same efficiencies are referred by Guercio and Bini (2017): 15% electric efficiency and 80% global efficiency.

Combined heat and power production based on ORC is making an impact on the market. There also seem to be good market prospects for micro-CHP systems and biomass micro CHP plants in particular, but there is still a lot of work to do (Obi, 2015; Guercio and Bini, 2017). Further research and development actions are needed to overcome technical and economical barriers, this resulting in commercialization of energy-efficient and low-cost micro-scale CHP plants. So far, one important driver for the diffusion of small size biomass CHP plants in Europe has been the incentives, but this needs to be accompanied by technology development and series production. Otherwise, a decrease in the investment costs will never take place. In the case of very small sized biomass plants, higher specific investments costs means higher production costs than with large-scale plants, but smaller sizes facilitates local consumption (Guercio and Bini, 2017).

At the 2018 edition of the annual Hannover Messe, Entrade Energiesysteme AG presented two versions of a high-performance model of micro biomass power plant. These patented models (25 kW and 50 kW) do not use combustion (direct-use) and steam turbine conversion technologies, but a gasification reactor in which biogenic waste is used to produce a synthesis gas that in turn fuels an internal combustion engine and supplies electricity and heat or even cooling. With a high efficiency of up to 85%, these plants can be combined with other renewable energy sources such as wind and solar energy to form a hybrid grid. In Figure 48, the E3 model (25 kW) is shown.

Figure 48.- High-peformance biomass power plant (E3) by Entrade.

2.5 SUBSTATION, TRANSFORMATION CENTRE OR DIRECT CONNECTION

Depending on the power capacity of the installation, as well as the use strategy and/or integration of the generated energy into the grid, important aspects should be considered. Thus, if the electricity generated is not going to be used in situ, it will be necessary to arrange a distribution network to transport the energy generated to the consumption points. In this case, there are two scenarios:

- Own distribution network. The operator of the energy generation installations feeds the energy into an own grid for its distribution to other points of consumption.
- Distribution network managed by third party. Depending on the power generated as well as the voltage of the distribution network, it would be necessary to have a substation.

Table 5.- Type of installation for feeding into the grid depending on power and voltage.

Nominal power	Voltage of the distribution grid	Type of installation of the connection	Complexity	Cost
P < 300 kW	400 V	Transforming centre	+	+
300 kW ≤ P ≤ 1 MW	12 - 55 kV	Substation	++	++
P > 1 MW	30 - 132 kV	Substation	+++	+++

3 BUILT IN [NON-CONVENTIONAL] RETS SUITABLE FOR NRAS

In addition to the more conventional energy sources and technologies that can be used for the generation of renewable clean energy, in the last few years a good number of research institutions are doing research on other less conventional forms of **harvesting energy -electricity- in roads**.

Conventional RETs only allow energy to be produced when the resources are available and the installation is feasible. On the other hand, the fact that roads are continuously subjected to solar and vehicle loads makes it possible the energy harvesting phenomenom: the generation of small amounts of power from unused and wasted energy. If properly implemented, the harvesting of this energy, otherwise dissipated over roads in the form of heat, vibration or deformations, could turn roads into a source of renewable energy (Guo and Lu, 2019; Jasim et al., 2019; Zahibi and Saafi, 2020). For the moment, these systems can supply electricity to street lamps, traffic lights, signals, information panels or sensors for structural health monitoring, the latter being more and more used in the road context (Figure 49).

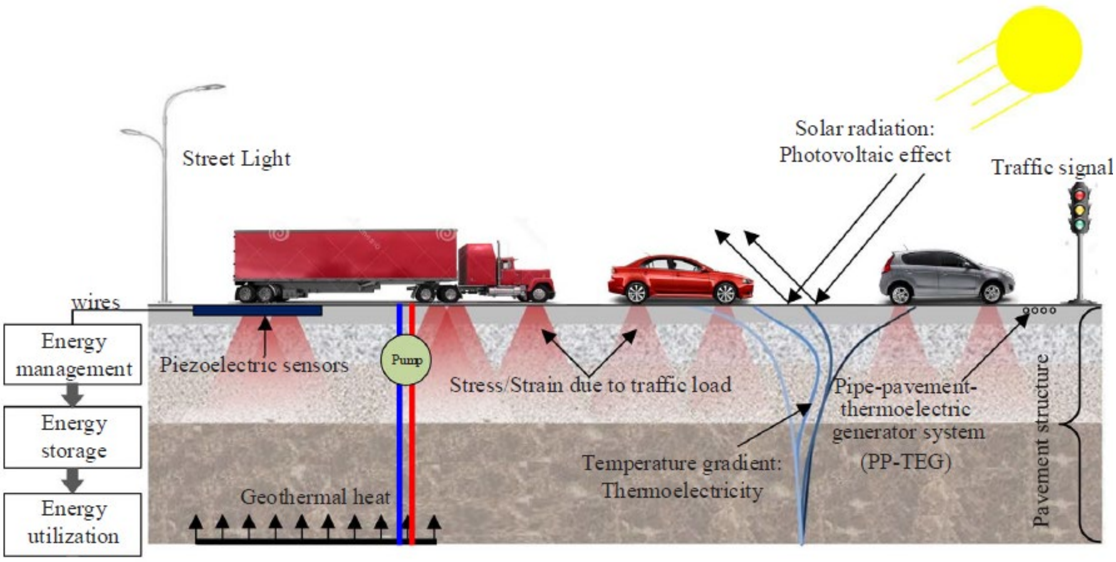


Figure 49.- Seebeck effect in a TEG module. Sources: Wang et al. (2018)

Based on the framework of this document and project, only the following road energy harvesting systems are here discussed:

- Solar energy harvesting:
  - Solar PV in roads
  - Thermoelectricity generation
- Kinetic energy harvesting (energy coming from the loads transferred by the vehicle):
  - Piezoelectric energy harvesting
  - Electromechanical or EM power generation

These technologies have been proved to perform when installed within the road asset, which means that renewable energy is actually generated by using these devices. As for the solar energy harvesting, not only will these systems provide some energy but will also help to mitigate the harmful effects of the heat on the pavement by removing it. Thus, important problems such as plastic deformation of roads (rutting), bitumen aging and hence, roads durability, or even the well known urban heat island (UHI) effect might be alleviated by removing part of the heat accumulated in the upper layers of the road pavement (Jiang and Huang, 2020; Zhu et al., 2019).

In general, the low performance and low energy generation of these energy harvesting technologies turn them into technologies difficult to apply at a commercial large scale. However, as they are road-related, their use in a near future is plausible and this document is mostly intended to provide knowledge, these technologies have been briefly decribed in this chapter according to the most recent technical literature. Likewise, the most relevant laboratory/small scale experiences so far have been briefly detailed.

3.1 THERMOELECTRICITY GENERATION

3.1.1 TECHNOLOGY

Thermoelectricity is one of the main forms of energy harvesting in roads. The installation of the so called thermoelectric generators (TEGs) within or aside the road surface makes it possible the conversion of the heat absorbed by the road into electrical energy (Jiang and Huang, 2020).

The principle of thermoelectricity is based on the ***Thermoelectric effect***, which is a physical phenomenon for which a temperature difference can be directly converted into electric voltage and vice versa by means of a thermocouple. Thermoelectric effect consists of three different but related effects: Seebeck effect, Peltier effect and Thomson effects. From the three of them, it is the ***Seebeck effect***, first discovered by the German physicist Thomas Johann Seebeck in 1821, the one capable to generate electricity from road pavements.

This effect is associated with the generation of an electrical voltage between the sides of a thermoelectric material (Figure 50). Two different types of thermoelectric materials (P-type and N-type) are connected to form a PN junction, and pairs of PN junctions are connected in series to form a thermoelectric module. In these materials, heat carriers are charged particles, which can be electrons in n-type or holes in p-type materials. When the two ends of the PN junctions are placed in different temperatures, the electrical charges displace from one side to another, creating electrical potential and an electromotive force (Jiang and Huang, 2020; Zahibi and Saafi, 2020).

The performance of the thermoelectric modules depends on parameters such as the thermal conductivity, the electrical conductivity, the temperature difference (ΔT) and the Seebeck coefficient (α), which is the ration between the change in electrical potential and the change in temperature.

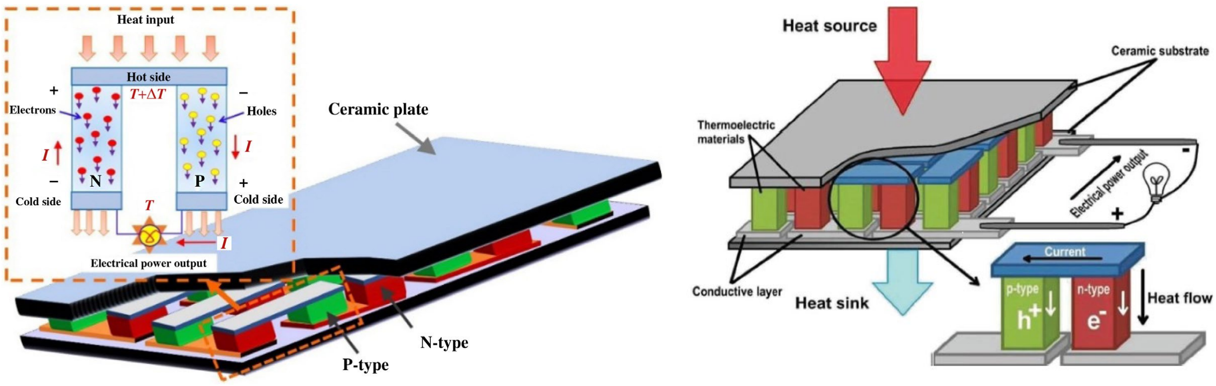


Figure 50.- Seebeck effect in a TEG module. Sources: Jiang and Huang (2020) and Datta et al. (2017)

The quality of the thermoelectric materials is described by a dimensionless figure of merit ZT, which is defined as follows:

$$ZT = \frac{\alpha^2 \cdot \sigma \cdot T}{k}$$

Where α is the Seebeck coefficient, σ is the electrical conductivity (1/Ωm), k is the thermal conductivity (W/mK) and T is the temperature difference. According to this equation (1), the greater the temperature difference between the two ends, the higher the ZT of the module. Regarding the materiales used for the thermoelectric modules, Bi_2Te_3, PbTe or SiGe provide high values of ZT (close to 1.0) but only the first one does it for temperatures under 150 °C (Zhu et al., 2019).

Finally, according to Datta et al. (2017), the following formula determines the generated voltage:

$$V = N \cdot \left(0.0002 \cdot 1.004^{\Delta T}\right) \cdot \Delta T$$

Where N is the total number of thermoelectric elements, which will depend on the module size (64×64 mm, 40x40 mm, etc.) and ΔT is the temperature different between sides.

<u>Forms of application and configurations</u>

As said by different authors, thermoelectric technology is an effective way of generating electricity from the energy that is accumulated in the asphalt road surface because of the solar radiation. There must be a temperature difference in the pavement structure, though, in order to apply this technology, something which not only depends on the solar radiation, but also in other parameters such as the air temperature, wind speed, ambient humidity and the thermal properties of the different asphalt layers. Thus, in latitudes where asphalt road surfaces can reach up to 60°C in summer time, the temperature at layers more than 10 cm deep can suffer a decrease of the temperature of more than 20°C (Zhu et al., 2019; Jiang and Huang, 2020), although these major differences do not last more than a few hours.

Two main forms of thermoelectric energy harvesting exist so far (to the knowledge of the authors of this document): the most common one, by using ceramic-based thermoelectric generators (Figure 51); and the second one, by using thermoelectric cementitious mixes (Zahibi and Saafi, 2020). While several small scale tests have been developed in the last few years (see section 3.2.2), the use of cement-based mixes with thermoelectric properties is still at a basic research level.

For the ceramic TEGs to work, a hot and a cold source is needed that makes the heat carriers move from one side to the other of the multiple PN junctions. In order to transfer the heat from the pavement to the TEG, two configurations are possible so far: the most common one, that makes use of the heat collected by the water flowing through a pipe network underneath the asphalt pavement; a another one that takes advantage of the very good conductive properties of metals by using a plate that transfers the heat from the pavement to the thermoelectric devices. In both cases, the cold source can be found at deeper layers of the pavement of even at a river nearby.

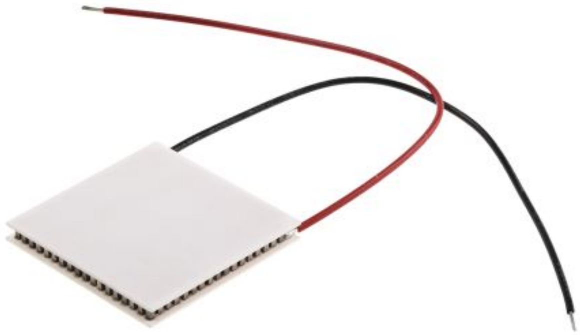


Figure 51.- Ceramic TEG module. Source: RS Components

In terms of functionality, a thermoelectric generator has several advantages: has no moving parts, allows continuous operation, and does not contain elements that must be replaced. On the other hand, the most important drawback is its low efficiency, with values in the range of 1-5% (Wu and Yu, 2012). Other crucial problem to be considered is the usual location of the thermoelectric device: in between of different layers of the pavement, with poor accessibility, exposed to traffic loads and hence, to potential degradation and lower durability. From the road point of view, including an odd element to the pavement structure, makes it more prone to damage. Therefore: accesibility to the TEG modules and influence on the road structure are two parameters that should be carefully taken into account. Thus, researchers such as Zhang et al. (2013), Datta et al. (2017) or Tahimi et al. (2019) decided not to place the TEGs within the road structure, but aside the road, keeping them connected to a metal sheet in contact with the asphalt pavement.

3.1.2 LAB SCALE OR SMALL SCALE CURRENT EXPERIENCES

Hasebe et. al (2006) developed a system in which Thermoelectric Generators are incorporated into the pavement to generate electric power. As heat source, this RTEC (Road Thermal Energy Conversion) system uses the heat collected by the water flowing through aluminium pipes embedded in the pavement. Then, this water is cooled down by river water (Figure 50).Thermoelectric power is thus generated based on the difference of temperatures between the hot water and the water cooled down by the river.

For the analysis of this system, a lab-scale prototype was built that comprised 19 thermoelectric modules and two heat exchanger tubes made of aluminium that enabled the temperature gradient. Power outputs of up to 9W were obtained for maximum temperature gradients (≈ 60 K) and 1l/min flow rates, however, when temperature differences more common to road pavements are considered (20-40 K), the power output critically drops to 1-2 W (Figure 52).

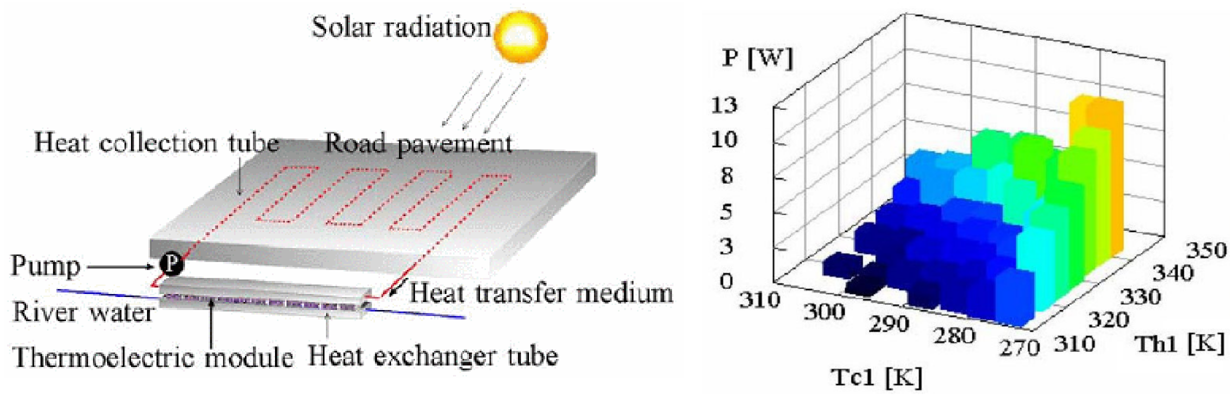


Figure 52.- Concept design and lab-scale experimental set-up. Source: Hasebe et. al (2006)

Some years later, a very simple experimental set-up for the thermoelectric energy harvesting in an asphalt concrete sample was developed by Wu and Yu (2012). In this case, an aluminium bar covered by a thermal insulator was passed through the asphalt sample, an intermediate aluminium plate was place on top of it and finally, a TEG was glued with thermal epoxies to the plate (Figure 53).

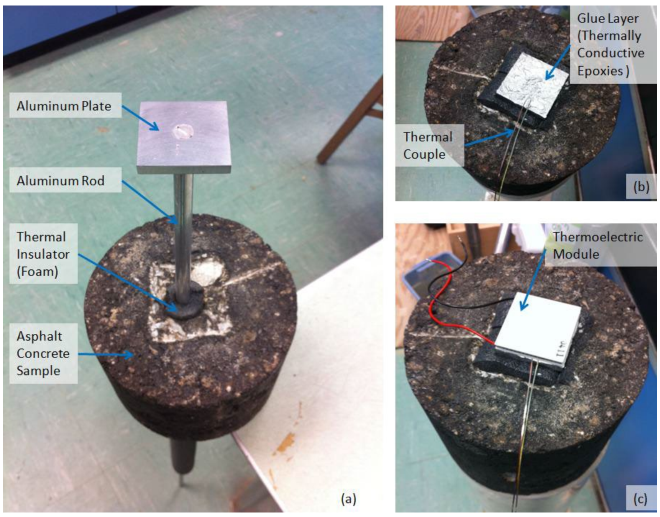


Figure 53.- Concept design and lab-scale experimental set-up. Source: Wu and Yu (2012)

The TEG was thus located at the asphalt surface, and a filament lamp was used to heat it up and create the temperature difference between the TEG and the aluminium bar. Up to 300 mV output voltage were generated per TEG cell, with power output of 0.05 mW per module (≈0.065 W/m2 assuming the asphalt sample is a marshall sample) and an overall efficiency of the energy harvesting system of about 2.05%.

A much more advance and interesting study was carried out by Datta et al. (2017). These authors made use of a Z-shaped metal sheet to conduct the heat from the core of the pavement to the TEG located aside the road. The prototype, which was evaluated under laboratory and field conditions, mainly consisted of the Z-shaped copple plate, a TEG located under the plate and connected to it, and a heat sink connected to the bottom of the TEG, which provided a relatively constant temperature over time (Figure 54).

The particular shape of the metal plate makes it possible that it works as heat collector (as one of its parts is embedded in the road surface layer), heat conveyor and heat transfer plate (thanks to its connection to the top side of the TEG).

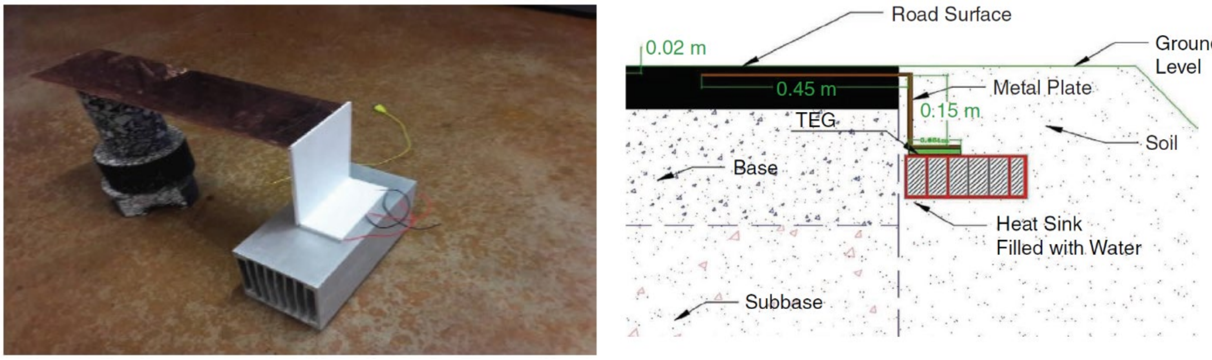


Figure 54.- Arrangement of thermoelectric prototype in the pavement. Souce: Datta et al. (2017)

Along with the laboratory tests, a field test was carried out in the asphalt pavement of the campus of the University of Texas at San Antonio. For this test a two-TEG and a four-TEG prototypes were used. Thus, two 500×175×37.5 mm strips were dug up at the edge of the surface layer in order to insert the top longest part of the metal plates. The other elements of the devices (remaining sections of the plate and heat sinks) were buried in the soil adjacent to the road edge. Data were collected between 1:00 and 4:00 p.m., from April to July 2016. Based on the measurements obtained, the two-TEG and four-TEG prototypes provided average output powers of 8 and 11 mW (≈0.09 and 0.13 W/m2), respectively, which yielded a very limited average energy generation of 0.5 kWh per day.

In terms of maintenance and harm to the pavement: 1) the accessibility to the TEG module is satisfactory, however, a more powerful installation would probably demand a much bigger area; 2) the flat metal plate is not as invasive as a pipe network for the pavement structure, however, it is still a an odd element and therefore, a source of potential damage.

Aimed not only at power generating but also at road temperature decreasing, Jiang et al. (2017; 2018) carried out and outdoor experiment to evaluate the performance of a new version of road thermoelectric generator (RTEG) in alleviating the urban heat-island effect while generating electricity (Figure 55). In this case, 3 mm thick, 300 mm long and 60 mm wide aluminium vapour chambers were embedded in the asphalt mixture at 20 mm depth in order to act as the heat conductor. Three modules with 199 pairs of thermoelectric components inside was used, one of which ends was connected to the exposed end of those vapor chambers and the other one to an aluminum vapor chamber placed at the bottom of a water tank. A shading board was erected to avoid direct sunshine and keep a water temperature consistent with the ambient temperature.

Figure 55.- Arrangement of thermoelectric prototype in pavement. Source: Jiang et al. (2017; 2018)

Tests were carried out in 2016 and 2017 in Xi'an (China), where the climate is temperate and temperatures reach up to 40°C and -5°C in summer and winter time, respectively. According to the results obtained at the end of May 2017, 1080 J of electrical energy were generated approximately by the 300 mm x 300 mm RTEG device (≈37 mW and ≈0.42 W/m2). Considering an asphalt pavement 1 km long and 10 m wide, up to 33 kWh electrical energy could be generated per day (scale effects not considered). Results also showed that the surface temperature of the RTEG asphalt in summer decreased up to 8-9°C when compared to a conventional asphalt surface.

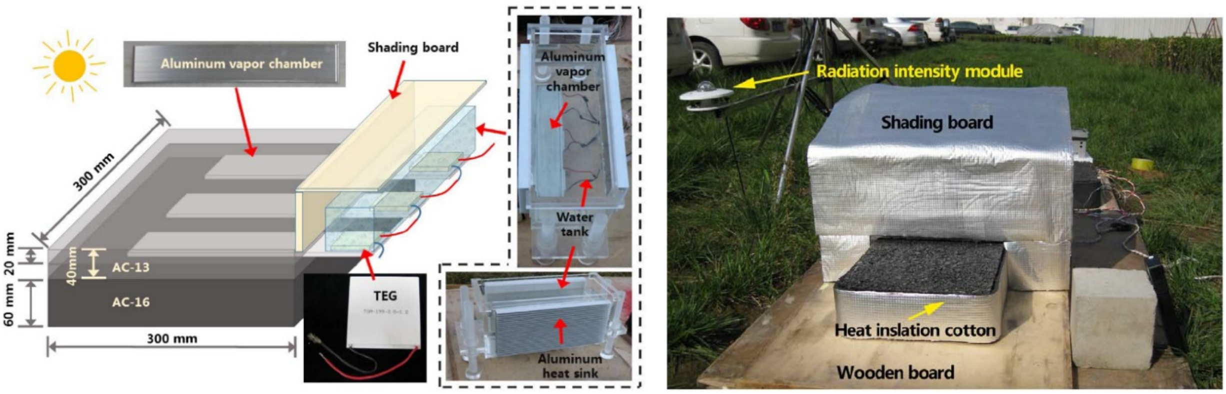


Figure 56.- Concept design and prototype for field test by Jiang et al. (2017; 2018)

Finally, Tahami et al. (2019) focused their research on enhancing the energy performance of the earlier Z-shaped TEG prototypes (Datta et al., 2017) by optimizing the heat transfer mechanism and defining a new cooling technique consisting of heat sink, insulation box and phase change material (PCM). In this study, the Z-shaped metal plate was replaced by a L-shaped copper plate 0,15 cm thick consisting of a horizontal

50 cm long heat collector, to be embedded 2-3 cm below the asphalt concrete surface, and a vertical 18 cm long heat conveyor attached to two TEGs (Figure 57). At the cold end of the TEG, a heat sink is attached that is filled with a phase change material (PCM) that is ideally suited for maintaining the temperature of the heat sink relatively constant. An insulation box acts as a thermal-barrier to prevent the exchange of heat between the heat sink and the soil aside the road in which it is buried.

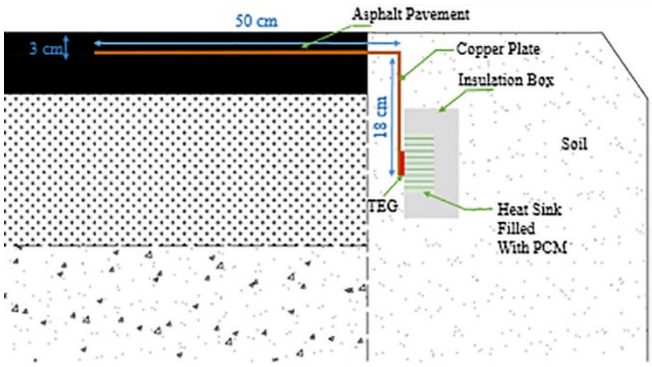


Figure 57.- Concept design and prototype for field test by Tahami et al. (2019)

For the field test, the copper plate was embedded at a 3 cm depth into a dense graded asphalt mix slab, and the heat sink and insulation box were embedded into a bucket filled with soil (Figure 8). Based on the measurements obtained taken on July 2019, the new cooling systems made it possible to produce an average power output of 29 mW (≈ 0.29 W/m2 considering an area of the prototype top plate of 0.5 × 0.2 m^2). This means trebling the power output of the Z-shape prototype (Datta et al., 2017). For a roadway 1 km long and 10 m wide, an energy generation of 23 kWh per day can be expected.

In addition to simply assembling TEGs modules, other researchers have focused on developing innovative cementitious thermoelectric mixes for power generation. Thus, additives such as metallic oxides or carbon fibers can turn conventional construction materials into energy generators. The research done by several authors on this topic can be found in Zabihi and Saafi (2020). The technology is still at an early stage of its development and cannot be considered at all for its use in the context of the ENROAD project.

In terms of costs, the thermoelectric energy generation is not economically competitive yet. When the Levelized Cost of Energy ($/kWh) is considered, the thermoelectric generation is more than 5 times more expensive than the traditional power generation (Tahami et al., 2019; Zahibi and Saafi, 2020).

3.2 SOLAR PV ON ROADS

PV panels are very well-known nowadays for converting incoming solar radiation into electricity. Although normally found in rooftops or displayed in big areas for solar collection, this technology is equally suitable for its use within the road asset in the form of conventional solar panels, flexible panels or even as built-in installations (i.e. the solar PV panel incorporated to the asphalt pavement as a surface layer).

A solar or PV cell is an electrical device that is able to generate voltage and electric current upon exposure to light by virtue of the photovoltaic effect. According to this phenomenon, when the light is absorbed by the cell, an excitation of an electron or other charge carrier to a higher-energy state occurs. More exactly, a solar cell consists of a P-type and an N-type semiconductors. When sunlight reaches the semiconductor materials, free electrons are forced to flow in such a way that negatively charged electrons move toward the N-type semiconductor while positively charged electrons move toward the P-type semiconductor. The flow of electrons creates an electrical current when connected to an electrical load (Wang et al., 2018).

PV Modules are a compilation of PV cells connected to each other in order to increase the energy output. A series of PV modules connected is called solar panel. Finally, a series of solar panels properly connected in order to generate electricity as a global PV system is called a solar array. When the light hits the panels, DC (direct current) is produced that is ultimately converted to usable AC (altern current) by means of an inverter system. **More information regarding PV technologies can be found in chapter 2**, including main properties, elements, materials, etc. As for the **road-related applications, the different attemps on this technology have been analysed in chapter 5**, where references to representative installations like those in USA, France or The Netherlands have been included as part of the study of the existing RET topologies within the road asset. According to the technical literature, solar roads are not economically competitive yet. When the Levelized Cost of Energy ($/kWh) is considered, solar roads are more than 50 times more expensive than the traditional power generation (Zabihi and Saafi, 2020).

3.3 PIEZOELECTRIC ENERGY HARVESTING

3.3.1 TECHNOLOGY

Motion of vehicles on the pavement generates a large amount of energy, a part of which is transferred to the road pavement resulting in deformation and vibration, with a portion of this energy wasted in the form of heat (Xiong and Wang, 2016). Piezoelectric energy harvesters (PEH) aim to convert mechanical energy in raods and bridges into electricity. The working principle lies in the piezoelectric effect discovered by Pierre and Jacques Curie in 1880, by which certain materials such as quartz, Rochelle salt and topaz can generate electricity when subjected to mechanical stresses (Sezer and Koç, 2021). The working principle of the direct effect of PEHs and its application to the road is shown in Figure 58.

Main properties governing the piezoelectric effect that should be taken into account for the selection of materials are the following: piezoelectric charge constant (d), permittivity (ε) and the electromechanical coupling factor (k) (Zabihi and Saafi, 2020). The piezoelectric charge constant is the polarization generated per unit of mechanical stress; the permittivity measures the polarizability per unit of electrical field; the electromechanical coupling factor is a measure of the conversion efficiency between mechanical and electrical energy (Chung and Petchsuk, 2013). In addition to the materials properties, other properties impact the piezoelectric performance such as temperature, direction and frequency of the load applied.

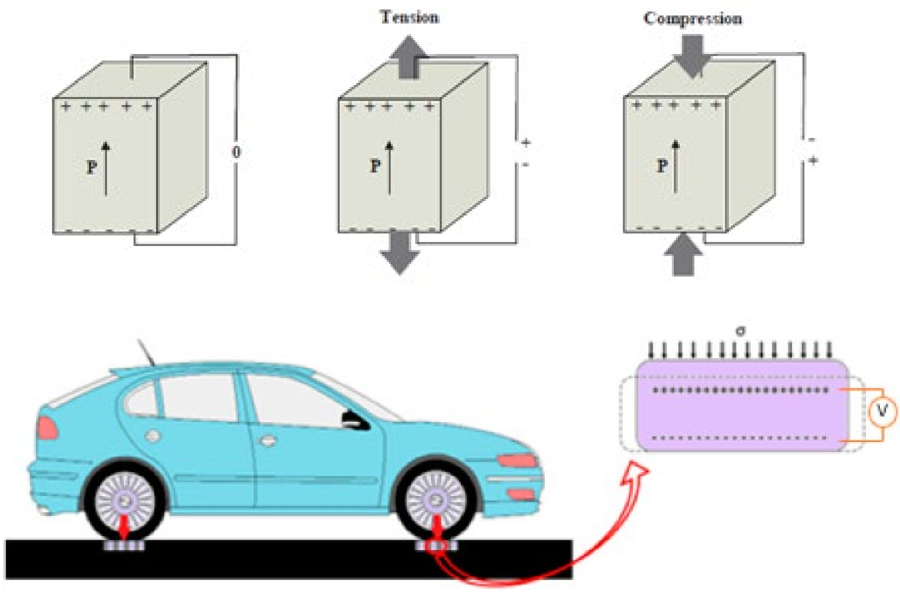


Figure 58.- Working principle of direct effect of PEHs. Sources: Wang et al. (2019); Zabihi and Saafi (2020).

Concerning piezoelectric materials, the most common ones are single crystals (i.e. quartz), piezoceramics (i.e. lead zirconate titanate (PZT)) and polymers (i.e. polyvinylidene fluoride (PVDF)). Piezoceramics exhibit high piezoelectric and permittivity coefficients as well as a high coupling factor. However, these materials are brittle and rigid limiting the amount of strain that can absorbed without being damaged (Sezer and Koç, 2021). On the other hand, piezoelectric polymers present less favourable piezoelectric properties but their higher flexibility and durability and their lower cost and weight make them more appropriate for many applications. To overcome the inherent brittleness of ceramics and the poor piezoelectric properties of polymers, new composite piezoelectric materials are being developed which consist in dispersing nanosized ceramics in a polymer matrix. However, the state of development of these materials is low.

In addition to the material selected, the geometry and design of the PEH will also affect the system performance. In this sense, several designs have been proposed, being the most common in the field of road energy harvesting the metal cymbal-shape, cantilever beam, disk and cylindrical piles, bridge and stack structure. The cantilever beam is a vibration-based energy harvester especially suitable for bridges, while the other configurations are recommended for stress-based applications such a roadways (Wang et al., 2019).

Although most the research shows PEH as a feasible and promising technology, the power outcome that can be obtained independent of their configuration and material properties is still low, within the range of milliwatts, suitable for small self-sustained applications . In addition, little investigation have been done concerning the effect on the durability of the pavement when a PEH is integrated within the pavement including the long-term durability and service life of the device itself (Wang et al., 2019).

3.3.2 LAB SCALE OR SMALL SCALE CURRENT EXPERIENCES

Few field scale experiences have been found in which the PEH are integrated in the road pavement and evaluated with real traffic since most of the research focus on the design of the PEHs and their laboratory testing and FEM simulation. Some results obtained from the different experiences are here presented.

Zhao et al. (2014) theoretically evaluated various shapes of PZT based transducers through FEM analysis for energy harvesting. A PEH prototype was designed using PZT piles (Figure 59) that according to the results might be able to harvest more than 50 kW/h from the pavement under heavy traffic. In this study, 8 to 16 PZT piles were recommended for one generator.

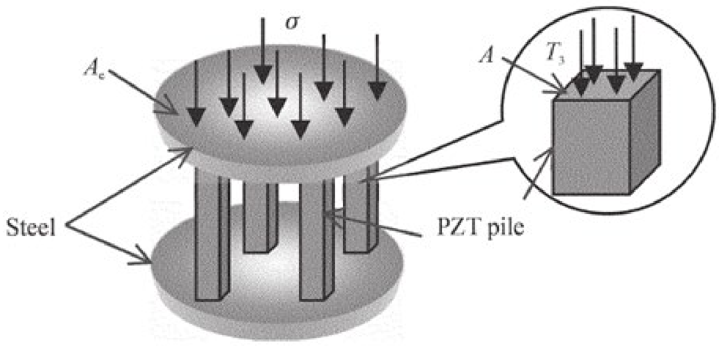
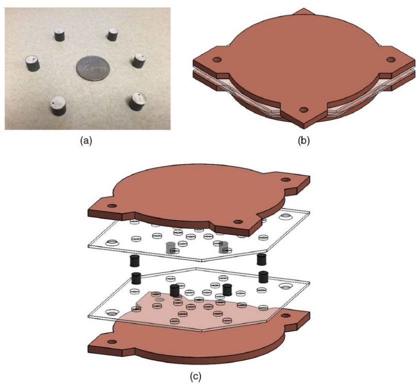


Figure 59.- Pavement generated prototype. Source: Zhao et al. (2014)

Roshani et al. (2018) designed two PEH prototypes (Figure 60) and tested them using a universal testing machine (UTM). Prototype I consisted of eight cylindrical PZT piezoelectric elements parallel connected through two copper plates and hold together with a polystyrene sheet. Prototype II was formed by a stack of 11 parallel-connected cylindrical PZT-4 disks with a diameter of 50mm and a thickness of 3mm.



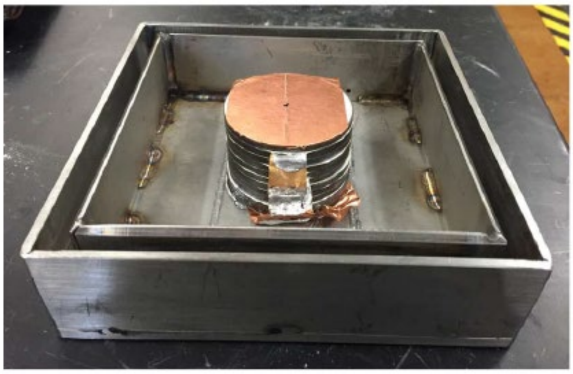


Figure 60.- Prototype I (left) and prototype II (right). Source: Roshani et al. (2018)

With the experimental data obtained at laboratory, rough estimations of the power output for real traffic loading conditions were done. Considering tire loads of 6.67 and 44.5 kN for cars and trucks respectively, the generated power from each car and truck passing at 64km/h was estimated in 33 and 1.487 mW for prototype I and 1.36 and 64.12 mW for prototype II. Thus assuming moderate traffic levels and installation of PEHs in the right-wheel path only, the estimated annual energy output was 360 Wh for prototype I and 171 Wh for prototype II. No reduction in power output was observed after 8 hours of repetitive loading.

A novel PEH was developed and field-tested by Xiong and Wang (2016). The PEH consisted of 850-series PZT piezoceramic disks sealed in a protective package. Six prototypes were installed at a weigh station with ≈4000 trailer trucks passing every day at an average speed of 40 km/h (Figure 61). The maximum obtained instant and average power output were 116 mW and 3.106 mW, respectively, and only 14.43% of the applied load was transmitted to the piezoelectric materials.

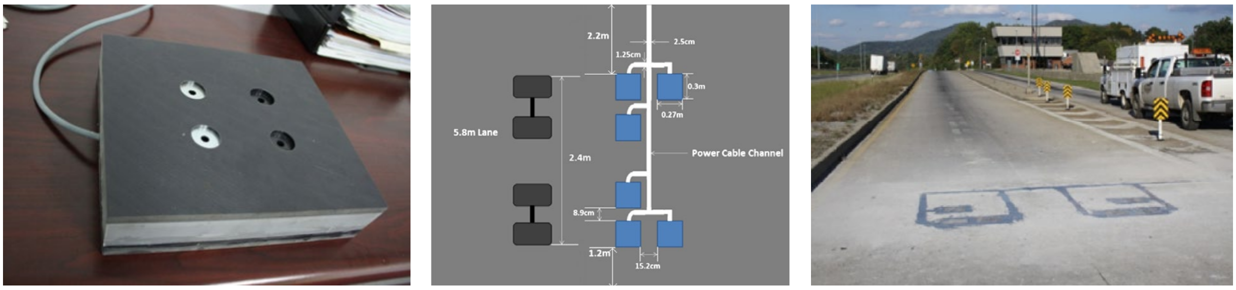


Figure 61.- PEH prototype, installation set up and PEH installed. Source: Xiong and Wang (2016)

Piezoelectric cymbals embedded in asphalt were evaluated by Moure et al. (2016). In this laboratory work, piezoelectric cymbals with commercial PZT ceramics were integrated in a host layer made of bitumen and silica filler (Figure 62). This mastic-cymbal system was placed under an asphalt surface layer of 2 cm and the power output of the PEH was evaluated in a wheel-tracking test to simulate the passing of vehicles. Each piezoceramic cymbal was able to recover up to 16 µW for the pass of one heavy vehicle producing around 12 V voltage peaks. For energy densities about 40-50 MWh/m2, with 30000 cymbals in 100 m of road, more than 65 MWh in a year might be generated according to the authors. The test was carried out during days without a reduction of the harvested power.

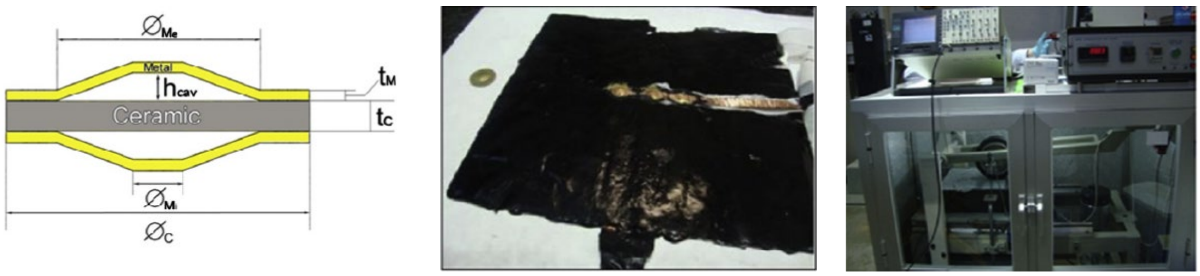


Figure 62.- Piezoelectric cymbal representation; cymbal embedded in asphalt mastic; wheel-tracking test set up. Source: Moure et al. (2016).

Flexible piezoelectric polymer-based PEH for roadway application has been developed and tested by Jung et al. (2017). The PEH module consisted of 60 PVDF films connected in parallel (Figures 63 and 64). The module was tested in the Model Mobile Load Simulator (MMLS3), achieving a maximum instantaneous power output of 200 mW across a 40 kΩ resistor. The power density reached up to 8.9 W/m^2.

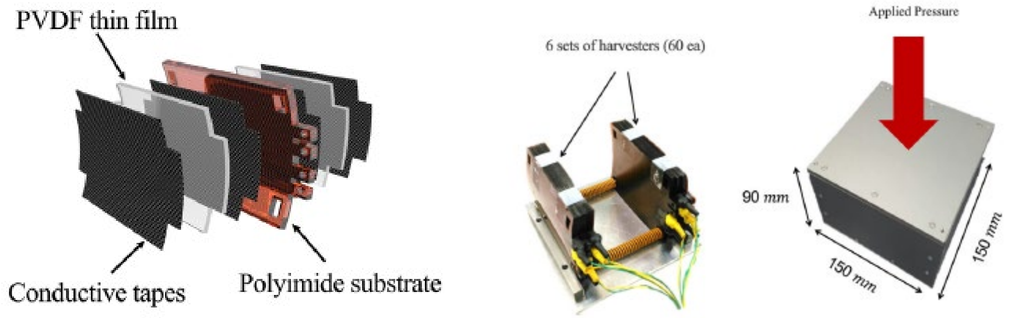


Figure 63.- Schematic view of PEH structure, interior and exterior of the module. Source: Jung el al. (2017)

Figure 64.- PEH module tested in the MMLS3. Source: Jung el al. (2017)

Yan et al. (2018) developed and evaluated a PEH module under real traffic. Two PEH modules were manufactured: a rectangular module with a thickness of 8 cm and a contact area of 30 cm x 30 cm and a circular one with a 30 cm diameter. Each module contained 12 piezoelectric units consisting in three PZT-5H slices stacked together and connected in parallel (Figure 65). A total of 20 PEHs (10 circular plus 10 rectangular modules) were embedded in the pavement of a test site. The open circuit voltage ranged 250 to 400 V when the speed varied from 20 to 80 km/h. The implemented PEHs could light a LED lamp at the end of the test section.

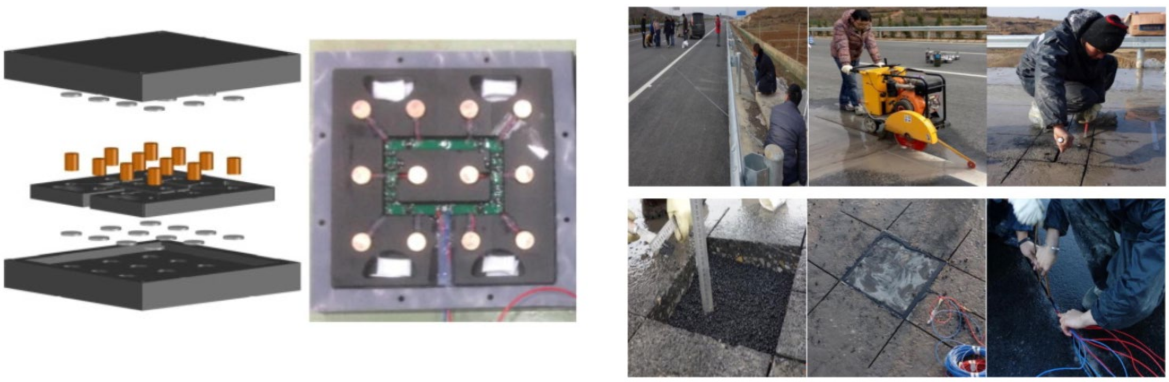


Figure 65.- PEH design (left) and installation process (right). Source: Yan et al. (2018)

A bridge PEH module was designed by Jasim et al. (2019). A total of 64 bridge transducers were assembled in 4 layers of 16 transducers in a 4x4 configuration (Figure 66). The impact of applied load and frequency on the piezoelectric energy harvesting performance was evaluated using single and cyclic loading events through a pneumatic loading system. The generated power output from one energy module under one pass of a simulated 39.5 kN dual tire was around 40-190 mW depending on the speed which might provide enough energy to low-power applications such as LED lights or sensors. By means of numerical simulation, it was found out that embedment depth and vehicle speed clearly affects the power output, as the more shallow the device is located and the higher the vehicle speed is, the greater the power output results.

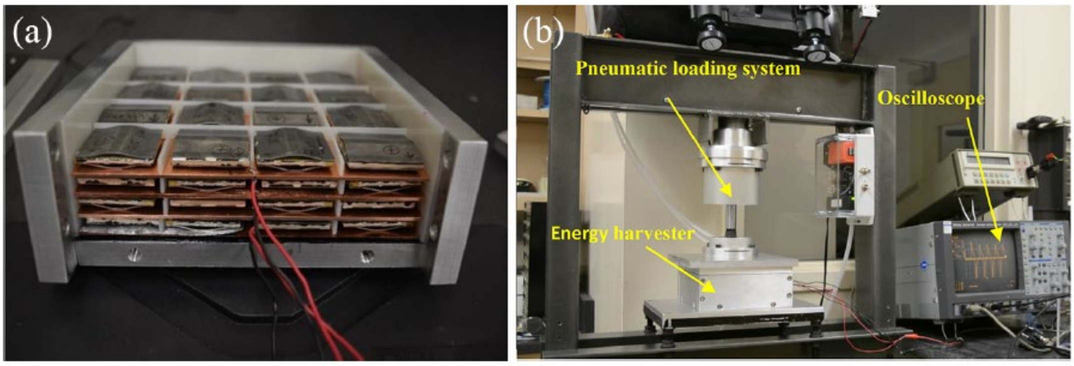


Figure 66.- Harvester module: array of bridge transducer and test setup. Source: Jasim et al (2019)

A PEH using piezoelectric cantilever beams were designed by Song et al. (2016). The harvester is designed to be placed under to surface layer (5 cm). This module consisted of PZT-PZNM ceramic units attached to a stainless steel plates (Figure 67). The PEH included a total of 12 cantilever beams. The output power was measured using a UTM limiting the displacement to 1 mm and setting the frequency to 10 Hz. An output power of 184 μW with a power density of 8.19 mW/m^2 can be generated.

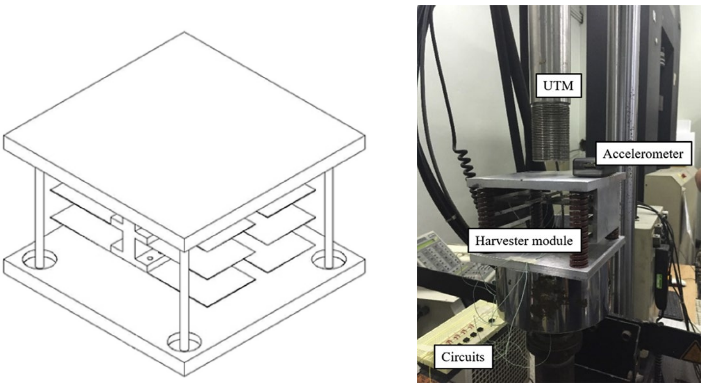


Figure 67.- Schematic view of the PEH; right: Experimental set-up. Source: Song et al. (2016)

A pilot research project carried out by the University of Twente (2012) on a regional motorway in the Netherlands investigated the feasibility of piezoelectric technology in a road pavement. The trial system was tested in 2011 and the results shown that the generated energy depends on the number of passing vehicles and the number of piezoelectric units in the road pavement. The amount of energy produced was not enough to be used in traffic lights or street lights but could be used for other less energy demanding devices such as motion sensors to detect vehicles.

Finally, the application of PEH in asphalt also captured the attention of the market. Innowattech (IPEGTM), Treevolt (POWERleap), Genziko and Pyro-E are some of the companies that have developed and in some cases patented PEH solutions for road application. Innowattech solution (Innowattech, 2010) consisted of piezoelectric generators, a harvesting module and a storage system. According to the company, around 200 KWh/h can be generated in 1 km section with 600 veh/h running at 72 km/h. On the other hand, the average energy generated by 1 km of installed Treevolt Piezoelectric Membrane System (POWERleap) is in the range of 400-600 kWh for 200 to 400 vehicles in 16 hour of traffic (Hill et al., 2013). No published results for the generated energy at laboratory or field tests are found for any of these claims. Innowattech seems to be out of the business nowadays.

In terms of costs, the piezoelectric energy generation is not economically competitive whatsoever. If the Levelized Cost of Energy ($/kWh) is considered, the piezoelectric generation is 500 times more expensive than the traditional power generation (Zabihi and Saafi, 2020).

3.4 ELECTROMAGNETIC POWER GENERATION

3.4.1 TECHNOLOGY

Electromagnetic harvesting is a phenomenon based on the Faraday's law of induction, according to which an electromotive force (EMF) is generated in an electric circuit or conductor by virtue of the influence of a magnetic field. Thus, Faraday’s law states that a current will be induced in a conductor which is subjected to a changing magnetic field either by moving the conductor in relation to the magnetic field generator or vice-versa. Although normally used in conventional power plants, smaller electromagnetic generators have been developed in the last decade that make it possible the conversion of waste energy coming from the vehicles, mostly vibrations and pressure, into electrical energy.

Roughly speaking, the electromagnetic harvesters consist of two elements: the electromagnetic converter in charge of the energy conversion, and the harvester unit in charge of collecting the mechanical energy and convert it into a rotational movement. Based on the latter, the different electromagnetic harvesters can be divided into hydraulic, pneumatic or electromechanical systems. Several different prototypes have been designed in the last few years to collect the unused energy from the vehicles, all of which have the same thing in common: the potential critical influence of the device on the traffic and therefore, the safety issues that may arise. Likewise, some of the devices proposed so far might result into physical damage for the vehicles passing over them. Thus, the use of EM harvesters in the context of the ENROAD project is difficult to conceive. In spite of this, some contributions have been very briefly described.

3.4.2 LAB SCALE OR SMALL SCALE CURRENT EXPERIENCES

An innovative energy harvesting system for roads called Waynergy Vehicles was developed in 2013 by the company Waydip in partnership with the University of Coimbra (Duarte et al., 2014). This system consisted of a 0.7 x 0.8 x 0.2 m3 block integrated within the surface layer of the road pavement. Inside, a mechanism capable of registering the small vertical displacement happening when vehicles pass over the blocks is enough to run an electromagnetic converter for its conversion to electricity (Figure 68).

Figure 68.- Field test of electromagnetic harvester prototype by Ferreira y Duarte (2014)

The prototype was installed in the access road to the parking of the Engineering Faculty of the University of Beira, in Covilhã (Portugal), where top speed was 50 km/h. Higher speeds are not recommended due to potential deterioration of the device. Results of the field tests shown that during one (peak) hour only 0,0105 kWh were generated, however, authors claimed that the electricity generated by several modules of the harvester possible located inside speed humps or bumps, could be used for storage, injection into the grid or even direct uses such as street lightning, traffic lights and information panels.

Zhang et al. (2016) presented a novel kinetic energy harvesting device to be installed at the entrance and exit of road tunnels. Main elements of the systems are: speed bump, suspension, generator and storage module. When a vehicle passes over the bumps, the kinetic energy is harvested by means of their upward and downward motion. This energy is then converted into electricity by the linear generator and stored in the batteries, ready for its application to road lighting, tunnel ventilation, EV charging, etc. (Figure 69).

For the field test, a full-size 2x2 arrangement of 1,00 m x 0,10 m x 0,375 m speed bumps were built, and a Volkswagen TUAREG SUV was used for the evaluation of its performance. Field tests were taken at passing velocities of 20, 30 and 40 km/h, the latter being the speed limit of the road. Peak and average voltages of 194 V and 55.2 V, respectively, were generated. Based on the voltages achieved, authors claimed that the proposed electromagnetic energy harvesting system is suitable for its use in roads and deemed to work well when higher speeds are required. On the other hand, no tests have been done for the analysis of the potential damage to the bump and/or the vehicle. The influence on the traffic when higher speeds are considered is not studied either.

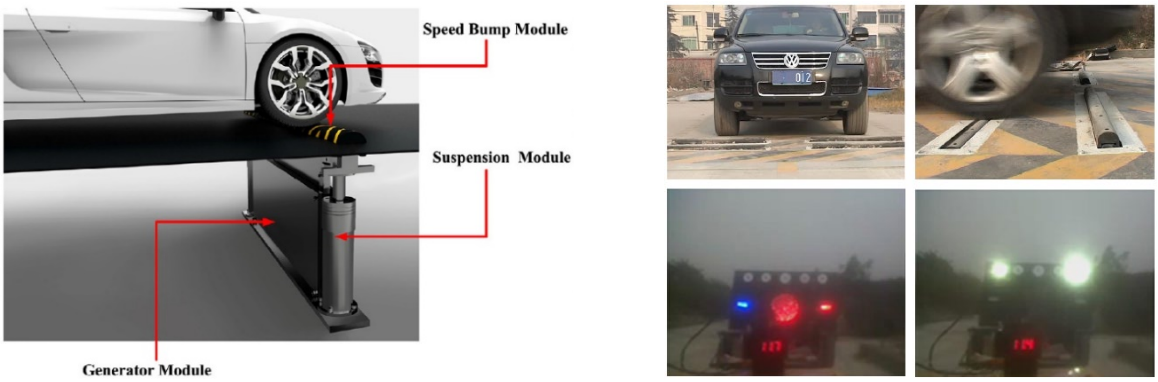


Figure 69.- Field test of electromagnetic harvester prototype by Zhang et al. (2016)

The rack and pinion electromechanical harvester designed by Gholikhani et al. (2019-1) has been another important contribution to the state of the art. This system included a top plate, racks, pinions, one-way clutches, a shaft, compression springs, supports and a generator. Once again, the top plate is the element that experiences the load and so it has to be properly designed from the structural point of view. Also the geometry is relevant, as the profile had to be similar to a speed bump. The combination of rack and pinion makes it possible the conversion of the vertical movement of the bump into rotational movement of the shafts inside the generator, which ultimately produces the electricity. A maximum average power of 3.21 mW was obtained during the laboratory tests, very low when compared to other recent references.

Two new electromagnetic energy harvesters were designed and tested at laboratory by Gholikhani et al. (2019-2), both of which resulted in better performance than the previous one. The mechanisms used for the generation of electricity were a cantilever generator and a rotational mechanism. Main elements for both mechanism were: supports, compression springs, a top plate, and a bottom plate (Figure 70). As in previous prototypes, the top plate was in charge of withstanding the wheel load while the springs coupled to the plate helped it to move smoothly under the vehicle loads.

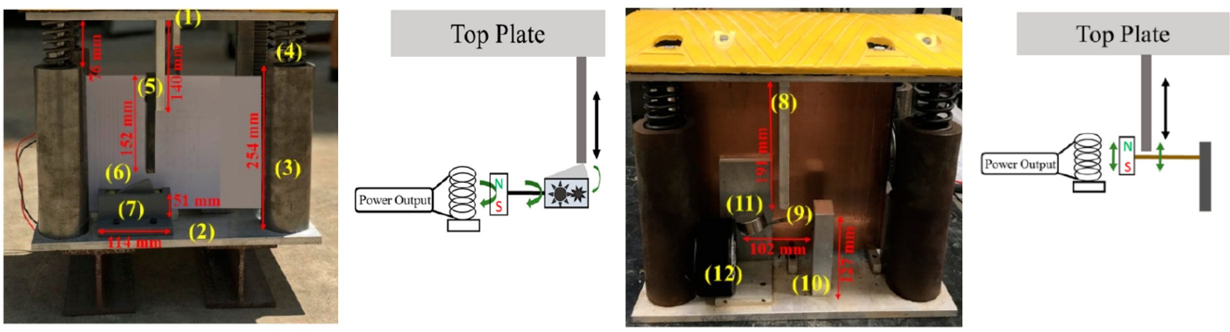


Figure 70.- Electromagnetic harvester prototypes by Gholikhani et al. (2019-2), *where: (1) top plate; (2) bottom plate; (3) cylindrical support; (4) compression springs; (5) two-part rod; (6) lever; and (7) box with magnets, coils, gears, and torsional springs; (8) rod; (9) spring arm; (10) arm support; (11) magnets; and (12) electrical coil.*

In the rotational mechanism a rod is connected to the top plate so that when this moves down the rod pushes a lever down. The vertical movement of the lever is then converted into a rotational movement by a set of gears and finally into electricity by means of the variation of the magnetic field. In the cantilever mechanism, when the rod moves down it pushes the spring arm down, which is a cantilever fixed to a support. On the free side of the cantilever a magnet is placed so that when the arm is pushed by the rod, a electrical current is induced due to the variation of the magnetic field.

As with most of electromagnetic energy harvester prototypes, no proper field tests were carried out, not even small tests at ambient conditions. Results shown that root mean square power of 0.4 W and 0.04 W and maximum power of 2.8 W and 0.25 W were reached by the cantilever and rotational sytems.

Other contributions to the topic can be found in Wang et al. (2018), Gholokani et al. (2019-2) and Zabihi and Saafi (2020). However, most of the applications have not been assessed in somewhat real conditions, some of them not even properly tested at a laboratory scale.

In terms of costs, the electromagnetic energy generation is not economically competitive at all. When the Levelized Cost of Energy ($/kWh) is considered, the electromagnetic generation is more than 100 times more expensive than the traditional power generation (Zabihi and Saafi, 2020).

4 BRIEF INTRODUCTION TO DISTRIBUTION SYSTEMS

According to the Electricity Market Report - December 2020 produced by the International Energy Agency (IEA, 2020), the global electricity demand in 2020 was expected to fall by around 2% due to the Covid-19 pandemic and its impact on the worldwide economy, this being the biggest annual decline since the mid-20th century. Likewise, the renewable electricity generation was projected to grow by almost 7% in 2020 according to the same report. In 2021, global electricity demand is expected to grow by around 3% under the assumption of the recovery of the global economy. In this context, the renewable power generation, in particular PV and wind energies, is expected to grow by more than 6%, taking the share of renewables to the 29% of the power generation mix.

Distributed generation is the term used when the electricity is generated from sources, often renewable sources, near the point of use instead of from centralized sources such as power plants. As the distributed renewable generation highly expands, there is an increased need for exploring the negative effects of that expansion on the power grid, one of which is the need to control the bidirectional power supply resulting from the fluctuating nature of the renewable energy. Besides, in the last few years more and more small consumers are willing to generate their own renewable energy and supply the excess power to the power grid, getting that back along the time and according to their needs (Ullah et al., 2020).

The combination of locally controlled renewable energy sources and energy storage systems is known as a microgrid. By virtue of their own nature, microgrids can help to mitigate the vulnerability of a potentially oversized power grid an provide simpler control, as the can disconnect from the grid when there is a main fault on the grid and keep on supplying energy to their local loads (Figure 71).

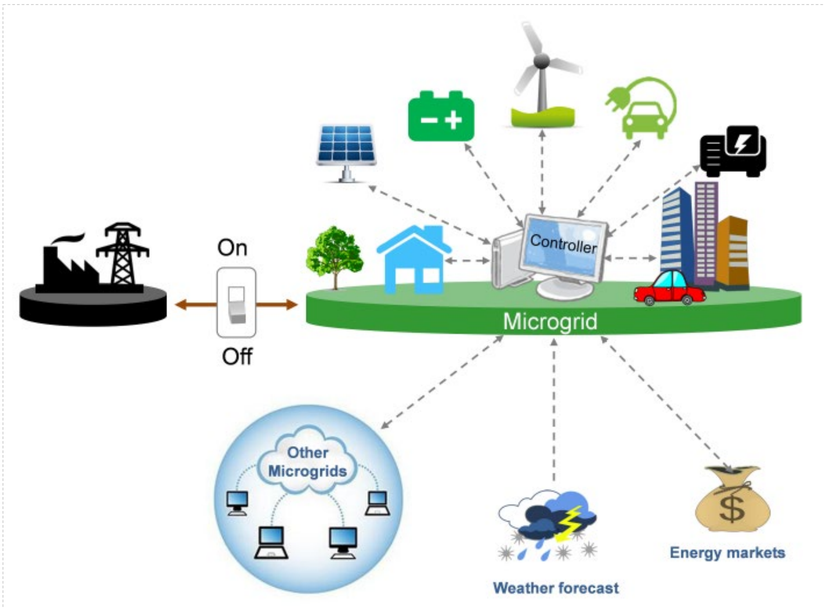


Figure 71.- Schematic design of a microgrid. Source: Berkeley Lab.

Smart microgrids not only can simplify the installation of new on-site energy generation devices such as solar PVs or wind turbines, but they can also provide enhanced control of the energy use at local level by enabling the connection of smart devices for monitoring purposes or provide intelligent services such as the charge of electric vehicles (Patterson, 2012). In summary, microgrids procure increased reliability and security of the power grid as well as increased availability of renewable energy and smart services.

So it seems that microgrids can help to deal with an extensive use of distributed renewable energy sources but, should the distribution systems and microgrids be AC or DC supplied? So far, available technologies have given AC systems a relevant advantage against DC systems: the fact that the voltage can be smoothly changed by means of a transformer, this resulting in high power transmissions over long distances at high voltages, reduced currents and lower line losses. However, dealing with DC systems today is much easier due to the continuous development of the power electronic converters, not to mention the fact that many industrial, commercial and domestic loads are DC supplied (Elsayed et al., 2015).

In general, supplying DC loads through AC distribution systems leads to high conversion losses due to the substantial number of power electronics devices required for the different conversion stages (Elsayed et al., 2015). Thus, almost 30% of the AC power generated in 2012 passed through power converters before it was used, a figure which would be increased in the following 10-15 years according to the author of the study (Reed, 2012). According to Patterson (2012), an energy loss in the range of 10-25% was expected. Likewise, the smaller number of power converters used in DC systems would decrease the manufacturing and installation costs of the installation (Ullah et al., 2020).

In the context of this project, DC is native to solar PV, battery storage and very convenient for applications typical of the smart microgrids. Therefore, DC/AC/CD conversions would be required in an AC microgrid including those elements. Based on this, DC microgrids including renewable energy resources and battery storage seems to contribute to the power grid stability and energy efficiency of the global system.

An interesting event regarding the use of microgrids has recently occurred in Austria, where the Austrian highway financing corporation ASFINAG in cooperation with the companies K.E.M. Montage and DHYBRID have implemented a hybrid microgrid at the Klagenfurt highway maintenance depot that combines a 220-kWp photovoltaic installation with a 522-kWh lithium-ion storage system (PV Magazine, 2021).

While main concepts and keywords have been here referred, the distribution systems and the microgrids in the context of the ENROAD project will be extensively covered in Deliverable 2.2.

5 CURRENT EXPERIENCES AND TOPOLOGIES

5.1 EXISTING EXPERIENCES WORLWIDE

Along with the renewable energy technologies that are suitable for their implementation within the road asset, location and topology are also crucial parameters to be taken into account in order for the NRAs to make the final decision. For the purpose of this project, **topology** has been defined as "spots, sites, pieces of furniture or road equipment, buildings, infrastructures, etc., along the road asset, where RETs can be installed, mounted, fastened, implemented, coupled, laid, etc.". On the other hand, **location** refers to the "geographical place (city, town, region, area, neighbourhood, etc.) where RETs can be installed depending on the different characteristics that are sought".

In order to determine potential topologies and locations for the implementation of RETs, a detailed search of previous experiences by the NRAs has been carried out including scientific papers, technical papers and brochures, information from institutional websites or repositories, news, etc. In Annex 1, a list with the most significant experiences worldwide found so far is presented. Size, power output or energy supplied have been considered, but also other parameters such as maintenance events, social importance, amount of information found and, of course, topology and location. Small or very small installations (e.g., small solar panels in traffic signals) and old unattended installations have been omitted too.

In addition to the information here provided, further information has been obtained through the ENROAD survey sent to the different NRA stakeholders (see chapter 6 and Annex 2). Thus, in the second part of the survey, recipients are requested to provide information about current experiences in their countries.

According to the inventory of current experiences found so far (Annex 1), the following 5 main groups can be distinguished based on the **technology** and **topology** involved:

1. Solar PV panels integrated into the road pavement (a.k.a. solar roads).
2. Solar PV panels integrated into the noise barriers (a.k.a. PVNB).
3. Solar PV panels/wind turbines in big areas aside or out of the road.
4. Solar PV panels/microturbines in rooftops of buildings or infrastructures.
5. Other.

5.1.1 PV PANELS INTEGRATED INTO THE ROAD PAVEMENTS (SOLAR ROADS)

To the knowledge of the authors of this report, only four countries worldwide host symbolic cases of these singular type of renewable energy technology: France, The Netherlands, China and USA. In France, China and USA one large-scale solar road was installed, while in The Netherlands several small to medium-scale have been installed so far. As for the technology, the same solar road design, Wattway, from the French company Colas, has been implemented in The Netherlands, France and USA.

In the Netherlands, at least 3 medium-scale solar roads (50-100 m long) have been developed in different municipalities or regions between 2014 and 2019. Thus, the provinces or Noord-Holland (twice) and Zuid-Holland hosted the construction of SolaRoad installation by the company Strukton Civiel.

The first stretch of SolaRoad, probably the first of a kind, was built in Krommenie (Figure 72), province of Noord-Holland, in October 2014. The installation, 90 m long and 3.5 m wide, was built on a bike path. The prefab modules were 2.5 x 3.5 m^2 and were overlaid with a hard plastic (initially tempered glass) top layer approx. 1 cm thick that protected them against mechanical loads and weather effects. The partners in the consortium at that time were: the research centre TNO, the construction company Ooms Civiel (Strukton Civiel since 2019), Imtech Traffic & Infra as the experts in electrical integration, and the Province of Noord-Holland as owner of the road (SolarRoad, 2021; Strukton, 2021; SolarRoad_UK, 2015). The total cost of the project was €3.5M, €1.5M of which were provided by the province of Noord-Holland (deorkaan, 2015).

Figure 72.- SolaRoad project in Krommenie, The Netherlands. Source: SolaRoad (2021)

A similar technology and construction process was used for the implementation of several more SolaRoad installations, the most significant of which were placed in Haarlemmermeer and Spijkenisse, a 50 m long parallel road with heavy traffic and a 100 m bus lane, respectively. In all these projects, the electricity was to be delivered to the grid. Two more small-scale SolaRoad stretches have been built in The Netherlands and other two in France (see Annex 1), but only 10 and 15 m long, respectively, and all of them bike roads (TNO, 2019; SolaRoad, 2021).

In addition to SolaRoad, there is one company that is very well-known for the development of solar panels to pave the road: Wattway. This company, set up by Colas, the road subsidiary of the giant telecoms group Bouygues (France), is the responsible for the technology of the solar PV panels used for the construction of solar roads in France, The Netherlands and USA. Wattway panels consist of PV cells that are embedded in a multilayer substrate composed of translucent resins and polymers that provides skid resistance and resistance to traffic loads (Figure 73). These very thin panels (7 mm) are actually glued directly on the road pavement and no milling is needed (Wattway, 2015).

The flagship project of Wattway is no doubt the solar road stretch built in the French town of Tourouvre, finished in December 2016. According to Colas, this 1 km road with 2800 m2 of PV panels and a maximum power output of 420 kW was aimed at generating 280 MWh per year. On average, the energy production should have reached up to ≈780 kWh per day, with peaks of up to 1500 kWh in the summer season (Patel, 2017). The energy goal of the solar road was the production of enough electricity to power street lighting for a town of 3400 residents (Guardian, 2016). The project, financed by the Ministry of Environment, had a cost of €5M, which means a cost of ≈12000 € per installed kW (Conversation, 2018). According to Colas, the cost to generate a kW with the Wattway technology was of about 17 €, way too expensive if compared to the cost of about 1.3 € of a conventional solar installation at that time (Pultarova, 2017).

Figure 73.- Solar road in France and Wattaway panels. Source: Guardian (2016)

In 2018, one more solar road project was born in The Netherlands in which the Wattway technology was used. In this case, it was BAM, a very important construction company in the country, which was in charge of the construction of the solar road on the N401 near Kockengen, province of Utrecht.

According to the company, the 50 m^2 stretch is able to generate enough energy as to provide a household with electricity during a whole year (BAM1, 2018). A second trial section was laid later on in collaboration with Rijkswaterstaat: a 20 m^2 strip of PV panels was installed on the emergency lane of the A2 at the end of 2018 that would be tested for two years (Rijkswaterstaat, 2021). Following, the characteristics of each of the solar panels used: area of 0.90 m^2, 28 solar cells, nominal output of 130 Wp and maximum voltage of the system 60 V (BAM2, 2019).

In order to know more about the monitoring and current status of the two test sections (see next section), **Gerben van Bijnen, Hoofduitvoerder at BAM Infra**, was contacted by email. According to Mr. Van Bijnen, the section on the N401 was removed as the test goals were achieved, but two other sections were built that are still running: a bridge deck (35 m^2) and a bike path (30 m^2) in the municipalities of Hengelo and Grave, respectively. Three more sections in the municipality of Hilvarenbeek are in preparation. Pictures of the four sections implemented so far are presented in Figure 74.

The lack of space in The Netherlands for the construction of big solar farms and the impacts associated to these farms are two important reasons for the investment on technological solutions such as the solar PV roads according to BAM. Supporting the generation of electricity by rooftop PV panels, which as stated in a research by Deloitte (AD, 2018), could meet 50% of the electricity demand in The Netherlands, is also a very good reason (BAM2, 2019). To the knowledge of the authors, three companies are potential suppliers of solar road technology in The Netherlands: SolaRoad, Wattway and Easypath.

In recent years, other small Wattway installations have been built throughout Europe (mainly in France) for applications such as electric car and bike charging. Thus, panels with total area of less than 70 m2 have been installed in in places such as Chalabre, Perpignan, Montpellier, Guyancourt or Narbonne, in France, or Sanem, in Luxembourg (Wattway, 2021).

Figure 74.- N401 road, A2 motorway, Hengelo and Grave, NL (top to bottom and left to right). Source: BAM

As for the Wattway technology overseas, two small test sections have been built in Georgia (USA) in the last few years. The first one is a 50 m^2 stretch built in December 2016 by The Ray in partnership with GDOT (Georgia Department of Transportation) and Hannah Solar. This test section is located next to the Visitor Information Center in West Point, Georgia (Figure 73), part of which is powered with the energy generated by the solar road (Ray, 2016). The Ray is a non-profit foundation aimed at making transportation cleaner and safer, but it is also a living laboratory located along the Interstate 85 for testing of new transportation technologies. According to the The Ray, more than 8400 kWh were generated in one year, enough to drive a single electric vehicle more than 50000 km (Ray, 2019-1).

The second solar road stretch in Georgia was installed in 2020 in the city of Peachtree Corners, in Gwinnett County, on a section of an autonomous vehicle test lane in the city's Curiosity Lab and has been provided through a partnership with The Ray (Figure 75). In this case, the energy generated by this test section, about 1300 kWh of electricity per year according to the company, is used to supply an EV charging station ant the City Hall that is available to EV motorists at no cost. As compared to the PV modules used in Normandy (France), these modules are supposed to be more durable and more efficient, this resulting in a 21% higher performance of the solar road section (Cities, 2020; What Now, 2020).

Unfortunately, no more relevant information has been found about the two installations in Georgia.


Figure 75.- Solar road in Visitor Information Center and Peactree Corners, Georgia. Source: The Ray

In China, another flagship solar road project was built in Jinan (capital of Shandong province) in late 2018. A 1 km stretch of a highway including two lanes and one emergency lane was covered with solar PV panels amounting a total area of 5800 m^2, twice the area of the solar road in Normandy, France (Figure 76).

Figure 76.- Solar road in Jinan, China. Source: NSEnergy (2019)

The solar road has three layers: a bottom layer for insulation purposes, a middle layer incorporating the PV cells and a top layer made of polymer able to withstand the traffic loads and proper skid resistance. It was estimated that 40000 vehicles per day would drive over this stretch built by Qilu Transportation, a state-owned company that in fact operates the highway. The panels were designed by the company Pavenergy.

In terms of performance, the road was able to generate and send to the grid 1 GWh of electricity a year, enough to power 800 households. However, the energy was used for the supply of street lights, billboards and CCTV cameras, as well as for melting the snow. As for its cost, estimates hover around the $2.7 million, which makes a cost of $460 per square meter approximately (NYTimes, 2018; LATimes, 2018).

A new project called Rolling Solar, coordinated by TNO and participated by 19 partners from Germany, The Netherlands and Belgium, including relevant companies like SolaRoad, Heijmans or Soltech, is running now in Europe (Rolling Solar, 2021). Its goal is to enable local manufacturers and construction companies to perform cost effective integration of long lengths of solar cell materials into public infrastructure. Two types of road elements are to be installed and compared. Likewise, three types of PVNBs will be installed and compared on an experimental scale. So far, the construction by SolaRoad of a road section based on crystalline silicon cells at Brightlands Chemelot Campus (The Netherlands) has finished. This test stretch is made up of 3 sections, 20 m^2 each: one with integrated monocrystalline silicon solar cell modules and another two section with integrated CIGS solar cell modules. The testing for electricity production and robustness is on going (Rolling Solar1, 2021).

5.1.2 PV PANELS INTEGRATED INTO THE NOISE BARRIERS (PVNB)

A good number of Photovoltaic Noise Barriers (PVNBs) have been installed in Europe in the last 30 years (also in other parts of the world like Australia or China, but at a much lower extent), the most relevant of which are here referred. Different reasons have been considered for their inclusion in this report such as the size, energy performance, availability of information from monitoring or social relevance.

The world's first highway photovoltaic noise barrier (PVNB) came into use in 1989 in the municipality of Domat/Ems, Switzerland, along the A13 road (Figure 77). This 103 kWp installation was supported by the Swiss Federal Roads Office (FEDRO) and built by the company TNC AG, based in Switzerland. The PV panels are fixed to a 2 m tall structure mounted at the top part of the 800 m long noise barrier (Poe et al., 2017).

Figure 77.- PVNB in Domat/Ems (Switzerland) in 1989. Source: TNC AG

Several other highway PVNBs were constructed across the country, FEDRO providing the infrastructure as long as the road safety is not compromised but never financing or operating the PVNBs facilities (Poe et al., 2017). One particular example of installation is the PVNB in Wallisellen near Zürich, which was built in 1998 by ARGE Borra SA and Atlantis Energie AG. This barrier was built face away the railway infrastructure (also applicable to the road infrastructure) using a Zig-Zag structure and combining sound reflection and sound absorption (Figure 76). The PVNB is South-West oriented and has a total length and height of 72 m and 1.4 m, respectively. At the time of its construction, it had a rated power of ≈ 10 kWp (Nordmann and Clavadetscher, 2004; SEAC, 2015).

Another relevant installation at that time was the PVNB in Aubrugg, near Zürich, which was built in 1997. This 8 kWp installation was the world first bi-facial PVNB and was made up of sound-reflecting PV modules designed by the company ASE GmbH (Figure 78). For the development of the modules, bifacial c-Si cells were put between two glass plates and then laminated together. A crane was used to insert the modules within the structure of a noise barrier placed on a bridge near a road junction, where other different roads run under and in parallel to the road with the barrier. The construction resulted in a 100 m long and 1.5 m high PVNB. In 2005 the barrier was expanded and update with more efficient bifacial cells (Nordmann and Clavadetscher, 2004; SEAC, 2015).

Figure 78.- PVNB in Wallisellen and Aubrugg (Switzerland). Source: Nordmann and Clavadetscher, 2004

Other important installation in Switzerland is the 100 kWp PVNB built in 1995 in Giebenach, along the A2 road. This barrier was installed facing away the highway and was able to produce 850 kWh/kWp electricity on average (Nordmann and Clavadetscher, 2004).

Two more PVNBs were installed and monitored in The Netherlands in 1995 and 1998 (Figure 79). The first one was located along the A27 highway, near De Bilt (Utretch). In this case, the PV modules were placed on top of a 590 m section of a noise barrier made of concrete. The systems had a total power of 48.5 kWp and the modules, with a tilt angle of 50°, were South-West oriented. The PVNB was connected to the grid, all the modules feeding one only large inverter, which was safely stored in a concrete housing along with the monitoring system. The total cost of the PV-project commissioned by the former Ministerie van

Verkeer en Waterstaat (now part of the Ministerie van Infrastructuur en Waterstaat) and built by Holland Scherm and R&S was € 1.106.094, of which € 544.536 was for the PV-system. (SEAC, 2015; Jochems, 2013).

The second PVNB was built along the A9 highway, near Ouderkerk aan de Amstel, near Amsterdam. It was a ≈220 kWp system comprised of 2160 c-Si modules on top of a noise barrier and with a tilt angle of 50°, each of them feeding a micro inverter. The grid connected barrier had a length of 1650 m and the total PV area was of 2200 m^2 approx. The project was financially supported by the European Commission and the Netherlands Agency for Energy and Environment (NOVEM), and had several partners such as NUON International / Duurzame Energie (coordinator and owner) or the Energy Research Foundation (ECN). The monitoring was carried out by ECN in co-operation with Fraunhofer ISE (Jochems, 2013; Nordmann and Clavadetscher, 2004; Van der Borg and Jansen, 2001; Photovoltaics, 2001).

Figure 79.- PVNBs in A27 and A9 (NL). Source: Betcke et al. (2002); Nordmann and Clavadetscher (2004)

A few years later, three more PVNBs were installed in Freising (Germany), Marano d'Isera and Oppeano (Italy) that result of certain interest for the purpose of this document. Thus, in 2003 the world largest PV sound barrier was installed in Freising (Germany), along the A92 highway. This 6000 m^2 and 1200 m long barrier (Figure 78) was the first one in which ceramic based PV modules (manufactured by the company ISOFOTON) with noise reduction properties were used and no conventional barrier was needed. In fact, two-thirds of the barrier was built with ceramic (Teflon) based PV modules and the remaining was filled with standard PV modules (at the bottom part) that had to be backed by a small concrete wall (Jochems, 2013; Grottke et al., 2003). The barrier is ablo to produce approximately 620 kW of electricity, which is sold back to the grid (Kotzen and English, 2009).

In 2009, a new PV noise barrier was built in Marano d'Isera (Italy), along the A22 highway. The installation was designed by IRIS lab and commissioned, paid and exploited by Autostrada del Brennero SpA. The barrier is 1067 m long and 5.6 m high (on average). The PV system is made up of standard c-Si modules, with top panels having a tilt angle of 35° and the rest of 60°, all the panels covering an area of ≈5000 m^2 (Figure 80). The barrier at Marano is still one of the largest in Europe, with a power capacity of 730 kWp and the electricity generation amounting 690 MWh a year, approximately. Aluminium panels are mounted on the rear part of the barrier for sound absorbing. The electricity, apparently used by a neighboring village, is fed into the medium-voltage 20 kV grid (SEAC, 2015; Jochems, 2013).

One year later, in 2010, a PVNB was installed in Oppeano (Italy) with a larger power capacity: 833 kWp. The barrier was designed by IRIS lab, built by FAR Systems SpA and commissioned, operated and exploited by ANAS, the Italian national road authority. The PVNB consists of two sections made up of standard c-Si PV panels, the two of them having different characteristics and geometries, and amounting a total length of ≈1 km (SEAC, 2015; Jochems, 2013).

Figure 80.- PVNBs in at Fresing (Germany) and Marano (Italy). Source: Wikimedia (Isofoton)

In 2014, a good example was shown in Zumikon (along the A52 motorway, in Switzerland) of how to make the most of the update of an existing noise barrier by also integrating a 80 kW PV systems on it.

Finally for Europe, the three more modern and therefore, representative PV noise barriers for the purpose of this report have been built in The Netherlands between 2017 and 2020. Unfortunately little information has been found about two of them. In 2017, the first of the barriers was built in Pijnacker-Nootdorp, along the N470 road, by the company BAM Infra. This 480 m long barrier was comprised of 240 panels, 200 Wp each, with total power capacity of 52,8 kWp. According to the company, the noise barrier should generate 30 MWh a year, all of which should be fed into the public grid (Solar Magazine, 2017; BAM, 2017).

In 2020, another PVNB was installed along the N470, between the cities of Zoetermeer and Delft, by the company Boksalis (Figure 81). The barrier, called Energy Wall, is claimed to provide energy for more than 300 street lights and 200 traffic lights along the road. The electricity generated by the barrier is stored in a battery and distributed by means of a DC grid (Zuid-Holland, 2021; Omroep (2020); Telstar (2020).

A lot more information exists about the bifacial PVNB installed along the A50 road near Uden, in southern province of Noord-Brabant (The Netherlands). This barrier was installed in the context of a European Life+ project called Solar Highways (Solar Highways, 2021), which started in 2014, ended in 2020, had a total budget of almost € 5M and was carried out by Rijkswaterstaat and TNO (still known as ECN). Thus, while the former was in charge of the soundproofing function of the barrier, TNO helped the Rijkswaterstaat with the development and implementation of the PV system. The company Heijmans Infra was awarded for its construction after a tendering process (SH Lyman, 2020; SH Final, 2020).

Figure 81.- PVNB between Zoetermeer and Delft. Sources: Omroep (2020) and Zuid-Holland (2021).

The noise barrier is 400 m long and 5 m high, and is formed by 4 m high PV panels over a 1 m high concrete plinth (Figure 82). The barrier was designed with 12 m^2 panels, each one consisting of two 3 m (wide) x 2 m (high) sections. The bifacial PV cells, produced in China, were connected to each other and laminated between two glass plates. Finally, the plates were fitted within a cassette by means of an aluminim frame. In December 2018 the noise barrier with the integrated bifacial PV cells was connected to the grid and became operational. The electricity generated is fed into the national grid. The fact that the PV panels are double sided results in an irradiation curve with a double peak, one in the morning and one in the evening, which results into a different energy output profile respect to conventional PV systems. To date, this barrier remains largest bifacial solar noise barrier in the world (SH Lyman, 2020; SH Final, 2020).

Figure 82.- PVNB in Uden. Source: Solar Highways (2021).

As said before, an interesting project is now running in Europe that is called Rolling Solar. In this Interreg innovation project, coordinated by TNO and participated by very experienced partners such as SolaRoad, Heijmans or Soltech, a double approach is proposed for the exploitation of the solar resource: solar roads and PVNBs. Regarding the latter, two experimental PV noise barriers have been installed so far (Figure 83) in Genk (Belgium) and Rosmalen (The Netherlands). The one in Genk is located at the Thor Park, and it is a 13 meters wide and 5 m high noise barrier that is built along a north-south road. This PVNB is divided in two different sections. In the first one, crystalline silicon and thin fim CdTe solar cell modules are mounted on frames over concrete, while thin film CIGS modules are glued directly into the concrete. In the second section (still ongoing), CdTe, CIGS and bifacial crystalline solar cell modules are integrated in metal frames. The PVNB in Rosmalen is 12 meters wide and is formed by 5 cassettes, one meter high each, on top of a 1 meter concrete plinth. Out of the 5 cassettes, two of them contain bifacial crystalline solar cell modules, one thin film CdTe solar cell modules and the remaining two contain double-sided thin film CIGS solar cell modules. The tests started at the beginning of this year 2021 (Rolling Solar 2, 2021).

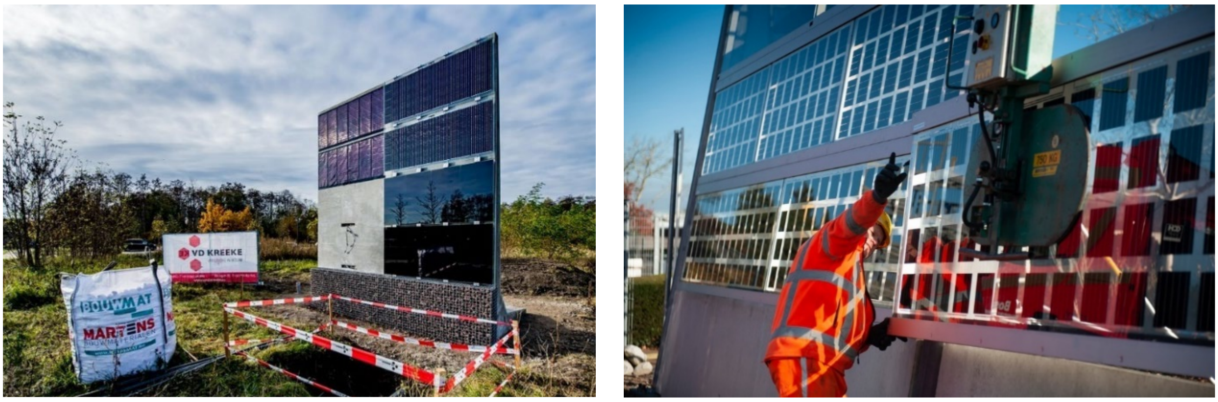


Figure 83.- PVNB in Genk (left) and Rosmalen (right). Source: Rolling Solar (2021).

Finally, the two PV noise barriers that have been built outside Europe are worth mentioning. Both of them were installed in 2007 in Australia and China. The installation in Australia is a 500 m long PVNB powered by the Roads Corporation of Victoria (VicRoads) and located at a highway interchange near the Melbourne Airport, in Tullamarine (Figure 84). In this barrier, the photovoltaic system is made up of 210 amorphous silicon panels that are vertically integrated on top of a 4 meters high noise barrier, all of them amounting a total power output of 24 kWp. The electricity generated is fed into the grid (Poe et al., 2017).

The PVNB located in China was installed along the route of a metro line in Shanghai. The barrier is 360 m long and 0.84 m high (Figure 84), and is comprised of amorphous silicon (a-Si) modules facing the railway. It was designed by Rail Transit Design Institute of Shanghai and has a power of 8 kWp (Gu et al., 2012).

Figure 84.- PVNB in Melbourne and Shanghai. Sources: Poe et al. (2017) and Gu et al. (2012)

5.1.3 PV PANELS AND/OR WIND TURBINES IN BIG AREAS ASIDE OR OUT OF THE ROAD AND/OR NRAS BUILDINGS

Several different types of projects have been developed in the last few years regarding the installation of mostly large scale PV panels but also wind turbines aside or out of the road. Most of these projects have been implemented in the context of the many lands that US Departments of Transportation manage and that are close to electrical loads, potentially making them ideal locations for the location of RETs. Thus, highway right-of-way (ROW) projects are claimed to add value to those assets, contribute to the reduction of GHG emissions, provide energy security by diversifying the sources and create green jobs (ROW, 2019).

In terms of the road topology, large scale PV panels or wind turbines have been installed so far: aside the road, in rest areas, service areas, aside NRAs buildings, NRA depots or even in former gravel sites. Thus, a lot of medium and large scale PV systems have been installed in the US within the lands of the different state's DOTs, the most relevant of which are in shown Annex 1. The remaining ones can be consulted in the thourough bibliography here provided. In addition to this, the most representative installations in the opinion of the authors of this document have been outlined.

In 2008, the Oregon Solar Highway Program of the Oregon Department of Transportation (ODOT) finished the first demonstration project of this kind in the US and probably in the world. In this project, a PV system with almost 600 panels and a total power capacity of 104 kW was installed at the interchange of Interstate 5 and Interstate 205 near Portland, Oregon. The energy generated was fed into the grid during the day and flew back from the grid to illuminate the infrastructure. The project is a public-private partnership between the ODOT and Portland General Electric (PGE). While the ODOT was in charge of the regulatory, legal and environmental requirements, PGE was in charge of the construction, operation and maintenance of the installation. Involving a private partner resulted in tax incentives (ODOT, 2016).

In 2012, the Baldock Solar Station was built at the French Prairie safety rest area, south of Wilsonville on Interstate 5 in Clackamas County (Oregon), a land property of the ODOT. The solar PV farm was comprised of almost 7000 panels, had a total power capacity of 1.75 MW and was able to generate 1.97 GWh on an annual basis (Figure 85). As the project before, the solar farm was developed in public-private partnership with PGE but in this case, the electricity produced is used by PGE to serve its customers, including ODOT, and in return for the land, ODOT receives an annual fee and a percentage of the RE certificates generated (ODOT, 2016; Innovative, 2021).

Several relevant actions have been taken by the Massachusetts Department of Transportation (MassDOT) in the last 10 years regarding the use of RETs along the road asset. Thus, after identifying almost 60 sites that could have been potentially used for solar PV generation, several projects were awarded in 2014 for the development of 6 MW or solar projects. In Figure 86 the ten projects initially awarded (in two phases) are shown, although three additional sites were sought to increase the generation capacity (Hodges and Plovnick, 2019; MassDOT, 2014).

Figure 85.- Baldock Solar Station at a safety rest area in Oregon. Source: Innovative (2021)

Phase	Location	Installed Capacity (kW DC)	Projected Annual Output (kWh)
Phase IA	Framingham I90 Interchange 13 N	649	735,706
	Framingham I90 Interchange 13 S	649	735,706
	Framingham I90 WB Service Plaza	318	360,485
	Natick I90 WB Embankment	271	307,206
	Plymouth Route 3 Exit 5	567	642,751
Phase IB	Salisbury, District 4 Depot	649	735,706
	Stockbridge I90 @ Interlacken East 1	649	735,706
	Stockbridge I90 @ Interlacken East 2	417	472,711
	Stockbridge I90 @ Interlacken West	649	735,706
	West Stockbridge I90 Exit 1	649	735,706
Total		5,467	7,107,100

Figure 86.- Actions taken by MassDOT for RE generation along the road. Source: MassDOT (2014)

In 2019, projects at eight sites were completed amounting a total power capacity of 4.3 MW. Most of this capacity (3.75 MW) was installed along the road (in the Right-of-Way) and only a small part (0.55 MW) in a solar canopy at the recently constructed Research and Materials Lab in Hopkinton. In August 2018, these sites had generated almost 11 GWh of electricity, this resulting in net savings of more than $1M. MassDOT expected to save $525,000 a year, in addition to the $75,000 received in annual lease payments for the sites, as all projects were developed in the framework of a public-private partnership for which MassDOT leased the sites for 20 years and agreed to purchase all the energy generated through power purchase agreements (Hodges and Plovnick, 2019).

Another solar array was set up in 2019 at the Exit 14 of the Interstate 85, in Georgia (Figure 87). This was the Southeast's first ROW project and was carried out in partnership between the Georgia Department of Transportation (Georgia DOT), Georgia Public Service Commission (Georgia PSC), Georgia Power, Electric Power Research Institute and The Ray. The solar installation has a 1 MW power capacity and counts on 2600 high-efficiency panels. Georgia Power signed a 35-year license with Georgia DOT for the exploitation of the property. The total cost of the project was of almost $3 million, including pollinator-friendly planting and LED lighting (Ray, 2018; Ray, 2019-2).

Figure 87.- Solar PV installation at the Exit 14 of the I-85 (Georgia). Source: Ray (2019)

One more installation is worth noticing despite the scarce information found. A solar garden has been developed by Novel Energy Solutions near the Interstate 94 in Afton, on a land owned by the Minnesota Department of Transportation (MnDOT). With a total area of 11 acres, the Afton Solar Array project is part of the MnDOT goal of increasing the RE generation in the state's energy portfolio. To this end, a former gravel pit has been used for the location of up to 3 MW of renewable energy (Figure 88) that will provide the MnDOT with a $500 lease payment per acre and energy savings from up to 40 percent of all the renewable energy produced on the site (MnDOT, 2020; Twin, 2020; Afton, 2020).

Figure 88.- Solar Garden in Afton (Minnesota). Source: MnDOT (2020)

Other installations highlight such as the 19-acre, 1 MW solar farm built under a public-private partnership in the Caltrans District 8 Transportation Management Center in Fontana, California (Figure 89). However, very little information has been found beyond the fact that it has reduced the energy demand of the local power grid by approximately two-thirds (ROW, 2019; Caltrans, 2020).

Figure 89.- Solar farm at Caltrans in Fontana (California). Sources: Caltrans (2020) and Google Maps

In Europe, the very remarkable and unusual “Wind Train” project started to operate in 2015. This project involved the construction of a wind farm to power the High Speed rail line between Leuven and Liège, in Belgium (Figure 90). The Greensky park is located along the rail line and the E40 highway and consists of 7 wind turbines with a capacity of 2 MW each, all of them commissioned by the end of 2015. Since 2017, the Licent wind farm, a second phase of the Greensky park, complements the initial turbines at Gingelom with 9 turbines of 2 MW each, spanning the municipalities of Orp-Jauche, Hélécine, Lincent and Hannut, and totally amounting 32 MW of wind capacity (Figure 90). The project is expected to reach up to 25 wind turbines with a total power capacity of 50 MW in different towns, provinces and regions of Belgium (Engie, 2021; Cogreen, 2021; Power Links, 2015; Renewables Now, 2017).

The wind park, has been constructed by Greensky scrl, a partnership between Electrabel (ENGIE), Société Intercommunale Bruxelloise pour l’Électricité, city of Saint-Trond and Infrabel, the Belgian government-owned company that builds, owns, maintains and upgrades the Belgian railway network. Greensky is also in charge of the operation and maintenance of the wind farm.

Figure 90.- Greensky wind farm, Belgium. Sources: Renewables Now (2017) and Engie (2021).

Assuming that these 16 turbines work 3000 hours a year, 96 MWh can be generated each year. Thanks to the connection of the wind farm to the rail network by way of the Avernas high voltage station, part of this energy can power the Belgian rail network, whereas the rest of it is fed into the national grid. Using this clean renewable was expected to save around 50000 tonnes of CO_2 emissions. (Infrabel, 2015; Power Links, 2015; Renewables Now, 2017). Performance updates from monitoring are shown in next section.

5.1.4 SMALL SCALE PV/WIND TURBINES IN ROOFTOPS OR ROAD STRUCTURES

Finally for the description of current experiences of RETs along the road asset, many small size solar arrays (mostly) but also small wind turbines have been installed in several other different places such as rooftops of buildings, canopies of parking lots or lands next to buildings facilities. References can be found of these installations as belonging to the different US DOTs:

- The **rooftop** of NRAs buildings, like in the Utah DOT Calvin Rampton Complex, among many others (Blue Sky, 2021; UDOT, 2018).
- At Missouri DOT's Conway Missouri **Welcome Center**, on the I-44 (Alternative ROW, 2012).
- At Ohio DOT's **maintenance facility** in Northwood, adjacent to the highway ROW, along the I-68 (Alternative ROW, 2012).
- At Texas DOT's **rest areas** (on top of 80-foot towers) in Gray and Culberson Counties (Sustainable Rest, 2017).
- The **canopy** of parking lots, like the solar canopy at the MassDOT Research and Material Lab in Hopkinton off of the I-90 road (ROW, 2017).
- The rooftop of buildings in **toll plazas**, like in the Coronado Bridge Toll Plaza at the Route 74 in California (ROW, 2019-2)
- **Other**: bus facilities, bridge facilities, bike paths and tunnels.

Regarding the small wind technology, turbines with 1.8, 1.2 x 2 and 32 kW power capacities were installed at Missouri, Utah and Ohio DOT's facilities, respectively, whereas 50 and 10 kW turbines were set in Texas, as seen in Figure 91. As detailed in the NCHRP report *Renewable Energy Guide for Highway Maintenance Facilities* (NCHRP, 2013), a tower-mounted 32 kW horizontal-axis turbine was placed at the maintenance facility of the Ohio DOT in Northwood (Figure 92), which was sized to meet 65% of the annual electric load of the 5400 m^2 building. With a cost of $200000 and a payback of 12 to 16 years, main concern was about timely maintenance and parts availability.

Also in NCHRP (2013), a tower-mounted 1.8 kW turbine was installed at the highway Maintenance Station of the Utah DOT in Milford (Figure 92). With a cost of $13500, the turbine functioned as expected and had no significant maintenance requirements. Annual savings of 3000-3500 kWh were estimated, leading to bill annual savings of $240-$280 and a payback period of 16 years (as the cost was covered with a US DOE grant). Several lessons learnt highlight such as properly forecasting the load requirements, including the potential load growth, and checking local ordinances early in the process to assess viability. Information on other small wind turbines installed by other DOTs is scarcer.

Figure 91.- Small wind turbines at Texas and Missouri DOT's facilities. Source: TRB ADC60 (2014)

Figure 92.- Small wind turbines at Ohie and Utah DOT's facilities. Source: NCHRP (2013)

Out of all the PV installations on top of buildings or road structures, three of them highlight for their size, visual impact and power capacity: the tunnel covered by PV panels along the A3 highway in Aschaffenburg (Germany), the bike lane covered by PV panels in South Korea and particularly, the high speed rail tunnel covered by PV panels in Belgium.

For the first two installations, very scarce information is available. The 2.7 km long tunnel along the A3 highway near Aschaffenburg (Germany) was completely covered by PV panels in 2009 (Figure 93). It was the largest PV system implemented within the road infrastructure, with a capacity of ≈2.7 MWp (Jochems, 2013; Volpe, 2012). Unfortunately, even less information has been found about the 20 mile long solar bike lane built in 2015 in the middle of a six-lane highway in South Korea, between the cities of Daejeon and Sejong, about two hours south of Seoul (Figura 92).

Figure 93.- Solar tunnel and bike lane in Germany and South Korea. Source: Volpe 2012

Finally, a very unique installation is shown in Figure 94. For this project, Infrabel and the solar developer Enfinity installed 16000 monocrystalline solar panels on the roof of a 3.4 km long railway tunnel between Antwerp and the Dutch border, along the E19 highway. With a 245 Wp capacity per panel, the amounts a total power capacity of 4 MWp (Reuters, 2011; Renewables Now, 2010).

Figure 94.- High speed rail solar tunnel between in Belgium. Source: Newatlas (2011)

With a cost of around 15M €, the PV system was completed in 2011. A production of 3.3 GWh of electricity per year was expected, equivalent to the average annual electricity consumption of nearly 1,000 homes. This energy was planned not to be fed into the national grid but to be used directly by the trains. According to Enfinity, solar panels used were manufactured by the Chinese company Jinko Solar and the return of the joint investment was expected to take place within 9 years (Reuters, 2011; Physorg, 2011; Newatlas, 2011). Performance updates from monitoring are shown in next section.

5.2 MONITORING OF CURRENT EXPERIENCES

Solar road by SolaRoad in Krommenie and Spijkenisse (The Netherlands) ***[see 5.1.1. – pp. 79-80]***

According to the monitoring performed by SolaRoad BV between November 2014 and June 2015, slightly more than 70 kWh/m2/year would be produced during those first months, with a generation of 4700 kWh of solar power for the 1st of June 2015 (i.e. seven months after the construction is finished). Based on the calculations by the company, this would provide the electricity to 2-3 households (SolaRoad_UK, 2015).

In October 2016 the bike path was expanded and some elements of the first generation were removed. However, several technical issues arised within the last few years such as the appearance of cracks on the plastic coating in 2017, which along with the lack of proper maintenance of the path eventually led to its complete removal by the end of 2020 (deorkaan, 2015; Wiki_SolaRoad, 2021; foryourinformation, 2020).

Figure 95.- Damage to the SolaRoad in Krommenie, The Netherlands. Source: deorkaan (2015)

As for other of the significant SolaRoad projects in The Netherlands, the 100 m long bus lane in Spijkenisse (Zuid-Holland), some technical issues arised too that made it necessary to close it only one week after its opening to the traffic in March 2019. The research done by SolaRoad found serious damage as the solar panel (the one with the cells) was detaching from the surface plastic layer, thus leading to deformation and further damage. Based on the nature of the damage, the province of Zuid-Holland refused to repair it put and end to the project (solar Magazine, 2019; Rijnmond, 2019).

Solar roads by Wattway in Tourouvre-au-Perche (France) and Utrecht (NL) ***[5.1.1. – pp. 80-82]***

Although no information has been found of an official monitoring by Wattway of the solar road in France, several other sources have reported on the deterioration and failure to generate the expected electricity. Thus solar panels degraded only after two years of the road construction as they were unable to withstand the loads from heavy vehicles. In addition to the premature wear of the new pavement, other deficiencies come out such as the clogging due to rotten leaves from trees or the required reduction of the speed limit due to the noise generated by the coating. A 100 m stretch had to be eventually removed as it was claimed too damaged to be repaired (GCR, 2019; Monde, 2019).

As for the energy generation, during the first year the solar panels generated ≈ 150000 kWh, which is half of what it was expected by the company (280 MWh, as said before). Besides, according to the BDVP, the French association for the promotion of solar energy, the generation dropped to less than 80000 kWh in 2018 and to less than 40000 kWh in 2019. On the other hand, as reported by the Orne council (where the town Tourouvre-au-Perche is located), the money obtained for selling the electricity was expected to be ≈ 10000 € per year, but in fact it was less than 5000 € in 2017, slightly more than 3000 € in 2018 and less than 1500 € during the first quarter of 2019 (Conversation, 2018; GCR, 2019).

Regarding the solar roads built by BAM Infra in Utrecht (The Netherlands) and other locations, the project developers were consulted about monitoring and current status. According to **Mr. Van Bijnen**, the results very promising were obtained on the N401 road in terms of electricity production and resistance to traffic loads of the panels. As said before, the test location was already removed. The results of the A2 motorway are also very positive, but the test is still on going. Sections in Hengelo and Grave are still properly running.

The panels were glued to the road surface and no important actions have been taken beyond the regular maintenance and cleaning with road surface cleaner. However, it was noticed that the roughness provided was not good enough, so the panels had to be removed and a new ones were glued with larger roughness by glass pearls. So far, these sections have not suffered from vandalism.

Solar road by Pavenergy in Jinan (China) ***[5.1.1. – p. 83]***

Very scarce information has been released about this remarkable construction beyond the figures given by NSEnergy (2019), which say that after the first 14 weeks of operation, a total amount of 96000 kWh of energy were generated, which is three times less than the expected average energy collection (assuming the potential 1 GWh energy generation per year previously stated). As for maintenance issues, only 5 days after the opening, a very small area (very few m2) of solar panels were reported to had been vandalised by thieves or stolen for industrial espionage purposes. However, new investigations concluded that a poor design might have resulted in damage by items falling or tossed from passing vehicles (SCMP, 2018).

PVNBs in Domat/Ems, Wallisellen and Aubrugg (Switzerland) ***[5.1.2. – pp. 84-85]***

After more than 25 years, the installation in Domat/Ems still delivered approximately 108 MWh per year to the grid once deduced the energy needed to power the PVNB monitoring system and the inverter, this making a 1000 kWh/kWp ratio. In terms of maintenance, a series of major interruptions occurred after 10 years of proper performance. Some components of the inverter had to be replaced too. Since 2002, the PVNB was back to work (Nordmann and Clavadetscher, 2004; Poe et al., 2017).

The PVNB installed in the municipality of Wallisellen, also grid-connected, generated 499 kWh per kWp in 1999, 2000 and 2001, this amounting a production of ≈5000 kWh electricity. A low performance ratio of 56% was observed probably due to several reasons such as: the influence of the shadows from trees and houses, the high temperature of the PV modules and the low efficiency of the inverters, among others. In terms of maintenance, some of the inverters broke down after several years and some PV cells had to be replaced as they were damaged. No PV modules or elements from the inverters were stolen even if they are easily accessible. No periodic cleaning was carried out as with the 45° angle of the modules, rain water is supposed to be enough. If necessary (Figure 96), slow running water should be applied (SEAC, 2015).

Figure 96.- Cleaning of the Wallisellen PVNB after roadworks. Source: SEAC (2015)

The PVNB installed in the municipality of Aubrugg generated 693 kWh per kWp between 1998 and 2001, this amounting a production of ≈ 5600 kWh of electricity. A low performance ratio of 58% was observed, which was probably due to several reasons such as: a low efficiency of the cells, a relatively low irradiation in winter and a low efficiency of the inverters. Because of the manufacturing process, one of the sides of the PVNB had a lower efficiency than the other. No vandalism was reported and no solar panel was stolen probably due to the difficult access to them (as being located in a bridge).

PVNBs in De Bilt and Ouderkerk-aan-de-Amstel (The Netherlands) ***[5.1.2. – pp. 85-86]***

The PV system in De Bilt (A27 highway, Utretch) was monitored between October 1995 and September 1997 in terms of the following parameters: DC yield, temperature and total power fed into the grid. In that period, the system was in operation 92% of the time, with performance ratios of 72% in the first year and 70% in the second year. The extra heating due to the metal sheets on the back of the PV modules (as compared to free-standing modules) might have led to a 1-2% lower efficiency of the installation. On the other hand, the non-ideal South-West orientation and tilt angle of the PV installation resulted in 18% less irradiation. The performance of the modules before and after cleaning them was evaluated by ECN after one year of operation. Results showed a 5.5% decrease in the performance of the installation due to the combined pollution from the traffic and the environment (SEAC, 2015; Betcke et al., 2002).

Regarding maintenance, security or safety issues, two reference cells for the monitoring were stolen only after two weeks as well as a PV module. In the following years, many panels were stolen and that were replaced with dummy panels. The easy access of the installation and the convenient size of the panels made them attractive to thieves (Figure 97). The PV systems is no longer operational (SEAC, 2015).

As for the PVNB installation in Ouderkerk-aan-de-Amstel (along the A9 highway), the monitoring task was carried out during the first 2 years of operation by ECN in cooperation with Fraunhofer ISE. In that period, a performance ratio in the range between 58% and 75% were obtained as well as an electricity generation in the range between 600 and 800 kWh per kWp (note that the installation had a power of 220 kWp). The results also showed a difference in the conversion efficiencies of the two different types of inverters used, which led to a 6% difference in the annual energy production of the PV modules. Energy losses due to the module temperature accounted for 4.5%. Finally, an assessment of the influence of the pollution on the PV panels was carried out by considering two weeks before and after the cleaning of the panels. Results showed that the dust on the modules accounted for an energy loss of 8 % (Van der Borg and Jansen, 2001).

Figure 97.- Several modules missing at the PVNB along the A27 highway. Source: SEAC (2015)

PVNBs in Freising (Germany), Marano and Oppeano (Italy). ***[5.1.2. – pp. 86-87]***

Performance and temperature of the two types of PV modules used in the PVNB in Fresing (Germany), ceramic based and standard modules, were measured. Results of the monitoring did not show a significant difference in terms of performance, with performance ratios of 0.71-0.76 and 0.70-0.75 for the ceramic based and standard PV modules, respectively. On the other hand, a difference of 5° C was found between the maximum temperature reached by the ceramic based PV panel and the standard panel. Finally, a small power degradation of 1.6% was estimated due outdoor exposure (Jochems, 2013; Grottke et al., 2003).

Unfortunately, no data about the energy performance of the PVNB in Marano or Oppeano is available (to the knowledge of the authors of this document). In the case of the barrier at Marano, no vandalism was reported on the inverters or cabling, but a few of the cameras installed were broken or missing and a glass of one of the modules was shattered according to the information in SEAC (2015).

PVNB along the A50 near Uden (The Netherlands) ***[5.1.2. – p. 87-88]***

After finishing the installation of the PVNB in Uden, its energy performance was monitored by TNO for a period of 18 months (from January 2019 to June 2020). The results showed that during the first year, 203 MWh of electricity were generated, this corresponding to a performance of 817 kWh per kWp. As claimed by TNO, this is enough to supply one year of electricity to 67 households or 14 km of highway lights. The total energy output of the 18-month period was 325 MWh, with an overall performance ratio of ≈74%. In Figure 98, the bar graph shows the monthly efficiency of the installation during the monitoring period. As expected, the amount of electricity produced in summer is much higher than in winter. This difference is bigger than with conventional -properly oriented- solar panels, though (SH Lyman, 2020; SH Final, 2020).

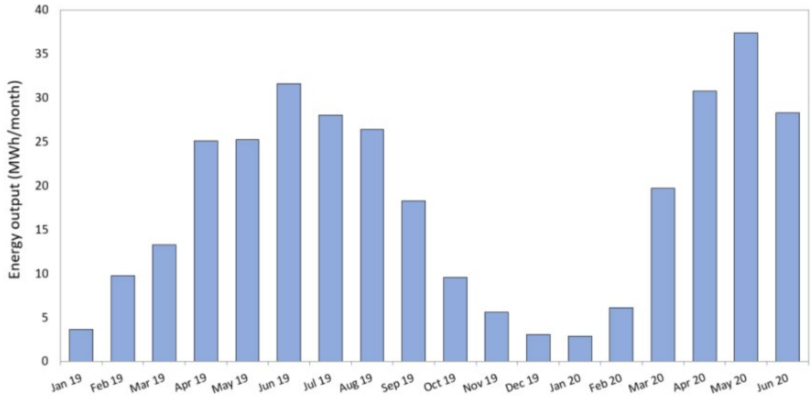


Figure 98.- Energy efficiency of the PVNB in Uden, from Jan 19 to Jun 20. Source: SH Final (2020)

The most up-to-date information on the energy yield of the PV noise barrier can be conveniently followed in a free access website (Solar Edge, 2021). According to the information in the website, slightly more than 15 MWh of electricity have been generated this month (March 2021), and a total of 456 MWh electricity have been produced since the PVNB started to operate (Figure 99).

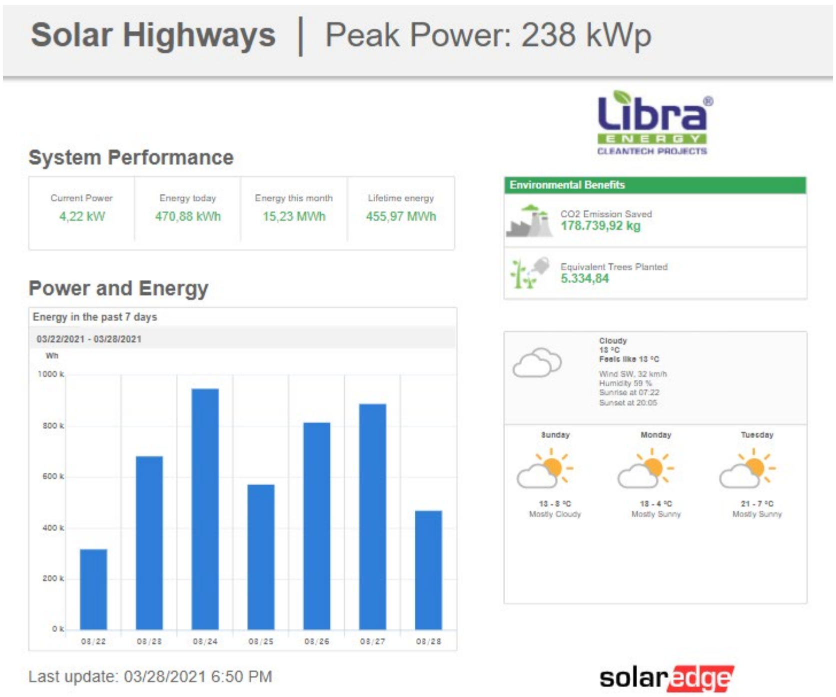


Figure 99.- Energy efficiency today (28 march 2021) of the PVNB in Uden. Source: Solar Edge (2021)

As for maintenance, security and safety events, graffiti has been observed in the barrier, but mostly in the concrete wall. During the monitoring, the area of the panel was covered with graffiti only once, this being quickly removed. Most importantly, several panels were damaged due to objects throwing although no effect on the energy efficiency was noticed, probably due to the quick repair operations (Figure 100). The cabinets containing the grid connection and electronics were also vandalized and later on, properly fixed.

Figure 100.- Vandalism events on the PVNB in Uden. Source: SH Final (2020)

Finally, as the primary function of a noise barrier is to protect the people from the noise generated by the traffic, noise levels and air quality were also monitored in October 2017. Due to the specific circumstances of the residental area behind the barrier (highway noise but also noise by residents in the area behind the barrier and noise from the nearby Volkel airport), the acoustic effects achieved after its installation were determined by means of sound calculation instead of measurements. According to the results obtained, a significant reduction of the noise levels was obtained when compared with a non-barrier situation, with a 18% reduction of area of noise levels above 50 dB. Regarding the air quality, the concentrations of NO_2, PM10 and PM2,5 slightly decreased (SH Final, 2020).

A very interesting conclusion from the Solar Highways project is that, based on the experimental analysis carried out, the barrier is not heavily affected by dirt and therefore, its cleaning (or the lack of) would not affect the energy yield. But even more important is the conclusion regarding the CAPEX for the PV barrier, which was much higher than expected and led to O&M costs higher than the income from using or selling the electricity generated, this eventually resulting in negative ROI and NPV (SH Final, 2020).

More information about the current status of the PV system was requested to **Stijn Verkuilen, Innovation Manager at Heijmans Infra**. According to Mr. Verkuilen, the system is still properly running (the electricity generation was slightly increased in 2020 as compared to 2019) and no serious incidents have happened in July 2020 (the time when the monitoring by TNO finished).

PVNB in Genk (Belgium) and Rosmalen (The Netherlands) ***[5.1.2. – pp. 88-89]***

The PV noise barriers in the framework of the the Rolling Solar Project (2021) are still under development and/or the monitoring has recently started.

PVNBs in Australia and China ***[5.1.2. – p. 89]***

A monitoring system was installed in the Tullamarine-Calder PVNB (Australia) that allowed the collection and transmission of the performance data to a VicRoads Control Centre. Unfortunately no data have been found so far. On the other hand, no maintenance, security or safety events have been observed according to Poe et al. (2017), probably because the panels are located at a height that makes it difficult any crash or theft and also because the inverters and wiring are accessible from the non-highway part of the noise barrier. Based on the the analysis carried out by VicRoads, PVNBs are not financially viable due to the low feed-in tariff for solar power in Australia at the time of the analysis. VicRoads found it more cost-effective to locate PV panels on the roofs of buildings due to the lower customization that it takes (Poe et al., 2017).

As for the PV noise barrier in Shanghai (China), a total annual average irradiation of 763.2 kWh/m2 was measured and an annual energy output in the range between 4274 and 5495 kWh was obtained. The low annual performance of 625 kWh per kWp resulted in a low capacity factor 7.13, which was claimed to be because of the orientation of the PV system (Gu et al., 2012).

Photovoltaic Systems in the Highway Right-Of-Way ***[5.1.3. – pp. 90-93]***

For the development in 2008 of the demonstration project by Oregon DOT at the interchange of Interstate 5 and Interstate 205 near Portland, transportation safety was carefully taken into account during location, construction and operation phases. The same happened with the electrical components: security fences, underground wiring, motion detectors and motion activated security lighting were used to ensure public safety and asset preservation. As a result, no safety or security issues were observed in the following years ODOT (2016).

The Baldock Solar Station generated 12% of the electricity needed by Oregon DOT in the Portland General Electric (PGE) service area. As before, safety and security issues were carefully considered: the PV system was left away from the freeway, traffic control was provided during its construction, and the same safety measures were applied to the electrical elements. As a result, no safety or security issues were observed in the following years ODOT (2016).

Wind Farm and Solar Tunnel by Infrabel (Belgium) ***[5.1.3. – pp. 93-94 / 5.1.4. – pp. 96-97]***

In order to collect information about the current status of the two flagships RE installations along the road (although for railway infrastructures) in Belgium, the wind farm and solar tunnel that supply energy to the Belgian rail network, **Bart Van der Spiegel, Energy Management from Infrabel,** was contacted. According to him, both installations are still properly working.

In order to provide the energy performance of the Solar Tunnel, the hours of use (ratio of yearly energy generation to installed power capacity) during the last few years were provided by Mr. Van der Spiegel: 833, 868, 898, 948, 912, 890, 988, 949, 968. As it can be deduced from this sequence, there is a fluctuation but not a reduction. So if any degradation have ever occurred to the PV panels, it has been compensated by extra hours of sunshine. These values are normal for Belgium. The power developed by the solar tunnel in February 2021 (late winter time) and June 2020 (early summer time) is shown in Figure 101.

To the knowledge of Mr. Van der Spiegel, no maintenance, safety or security issues haven been observed.

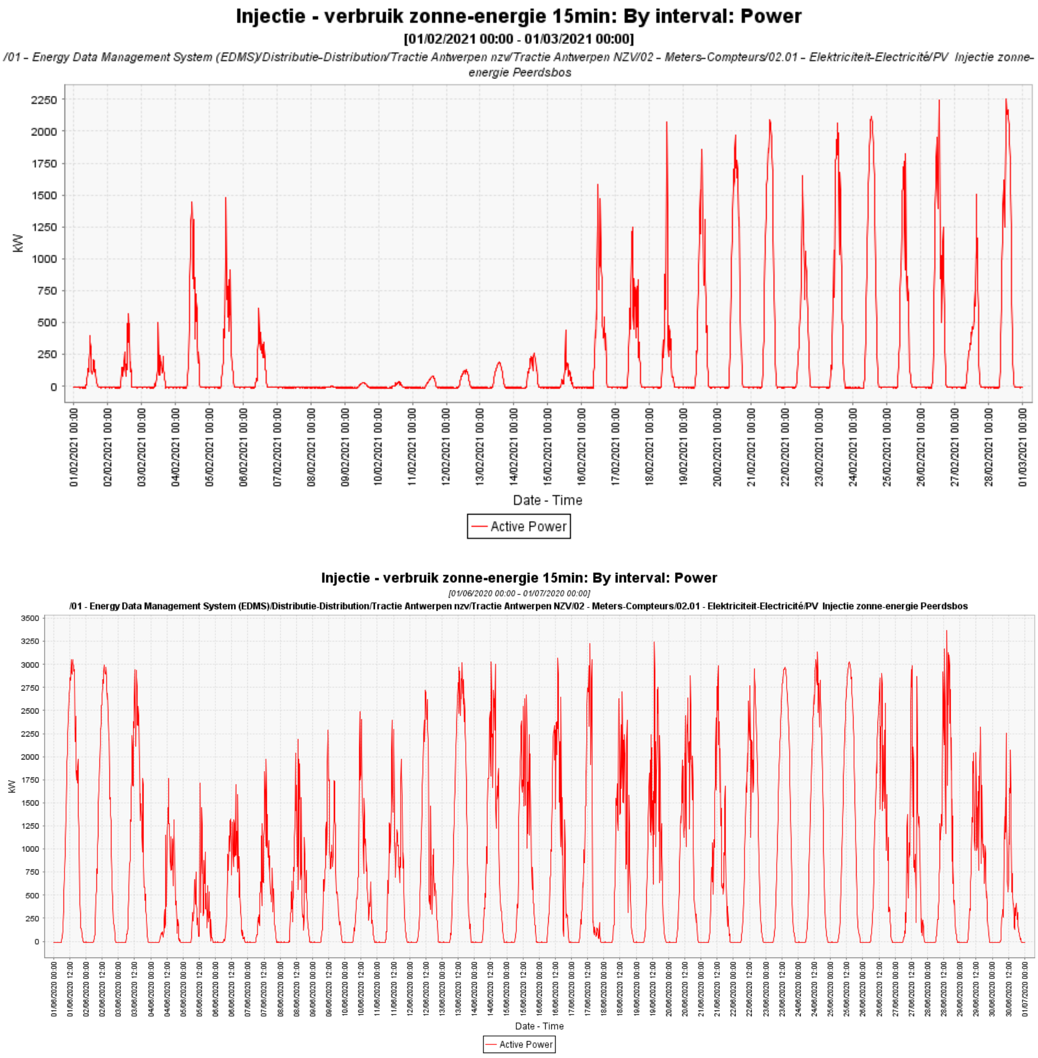
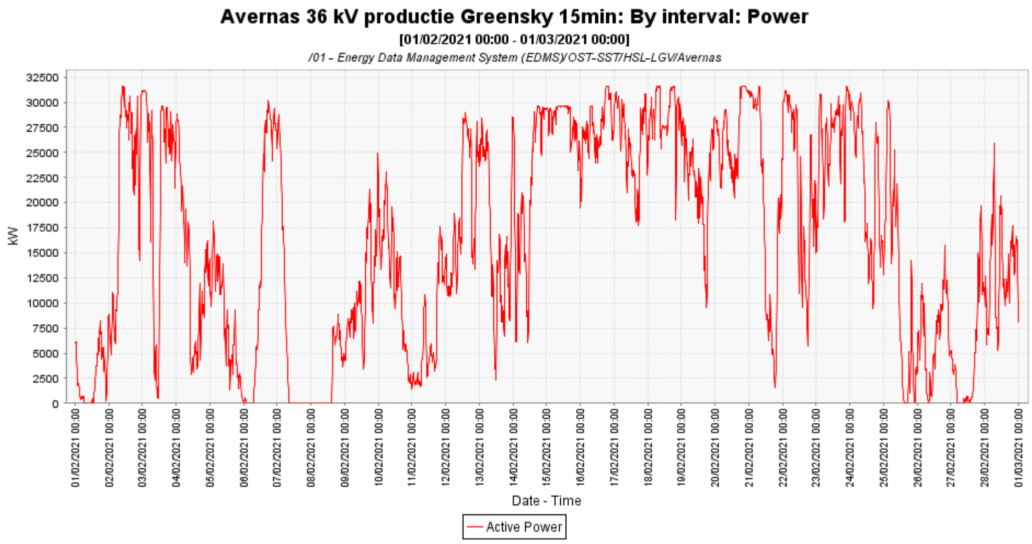


Figure 101.- Power developed by solar tunnel in February 2021 and June 2020. Source: Infrabel (2021)

Likewise, in order to provide the energy performance of the Wind Farm, the hours of use (ratio of yearly energy generation to installed power capacity) during the last few years were provided: 2379, 2909, 3194 and 3445. As it can be deduced from this sequence, the yearly production has increased due to the higher amount of wind. As before, these values match the normal values for a wind farm situated more than 100 km away from the coast and not on top of a hill.

According to Mr. Van der Spiegel, the reduced number of forests and buildings in the area contributed to the good results for these small wind turbines. The 16 turbines are 2 MW each, which was due to the long procedure to get all permissions (different regions, developed as a kind of private grid behind a substation of Infrabel connected to a federal voltage level). The power developed by the wind farm in February 2021 and February 2020 is shown in Figure 102. As it can be seen, sometimes the total power is limited to 30 MW, which means that in those cases one of the turbines was not working.



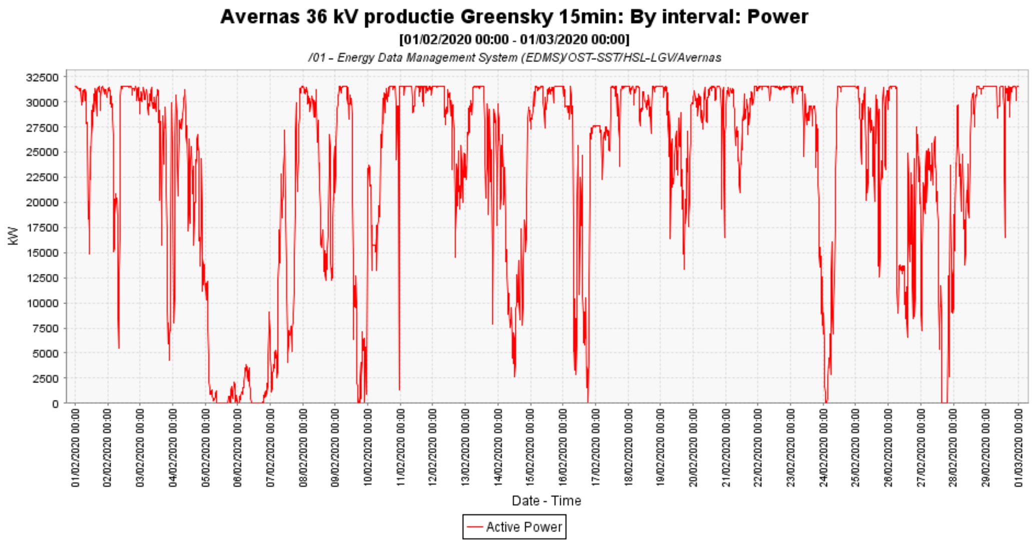


Figure 102.- Power developed by the wind farm in February 2020 and 2021. Source: Infrabel (2021)

To the knowledge of Mr. Van der Spiegel (note tha Infrabel is not in charge of the wind park maintenance), no issues regarding maintenance, safety or security haven been noticed.

6 RESULTS FROM THE ENROAD SURVEY

6.1 DESIGN AND PARTICIPANTS

As explained in the report for the justification of Milestones 2.1, a survey has been designed and sent to several NRAs stakeholders in the EU in order to: 1) test their interest on the topic; 2) collect information about their environmental targets, if any; 3) collect their opinion on the criteria used for the selection of RETs, topology and locations; and 4) collect information about previous experiences on the topic. For the design of the survey, the simplest and minimum possible number of questions were defined in order to collect as much information as possible. Likewise, the professional free software Limesurvey was used so that the survey could be filled out and the answers sent from a computer or even the mobile phone. The complete list of questions can be found in Annex 2.

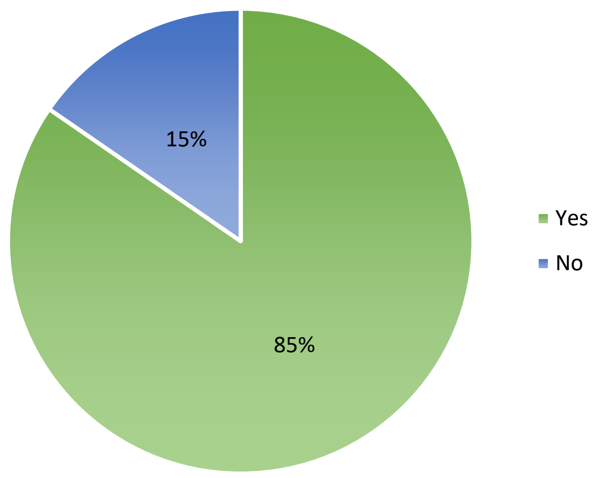
The link to the survey (along with a brief explanation of what the ENROAD is about) was sent to at least two representatives of NRAs of the following 17 countries: Spain, France, Italy, Belgium, Ireland, Sweden, Netherlands, Norway, Germany, Austria, UK, Portugal, Hungary, Rumania, Poland, Latvia and Denmark.

So far, 18 representatives from 13 different countries have sent a complete (mostly) or partial answer to the survey. One representative from another country entered the survey but did not go along. Finally, one more representative from another country kindly refused to answer the questions becuase its country is not part of CEDR.

6.2 MAIN RESULTS FROM THE SURVEY

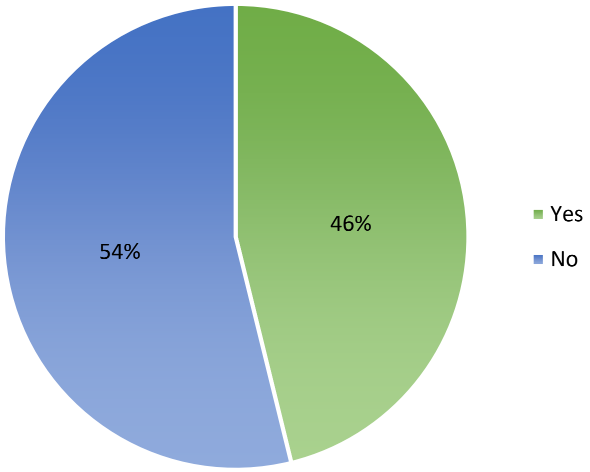
GENERAL QUESTIONS (Q1-Q12)

Q1.- Does your organization have internal targets to reduce energy use and/or GHG emissions?



Note: Inputs of the 18 representatives have been classified by country.

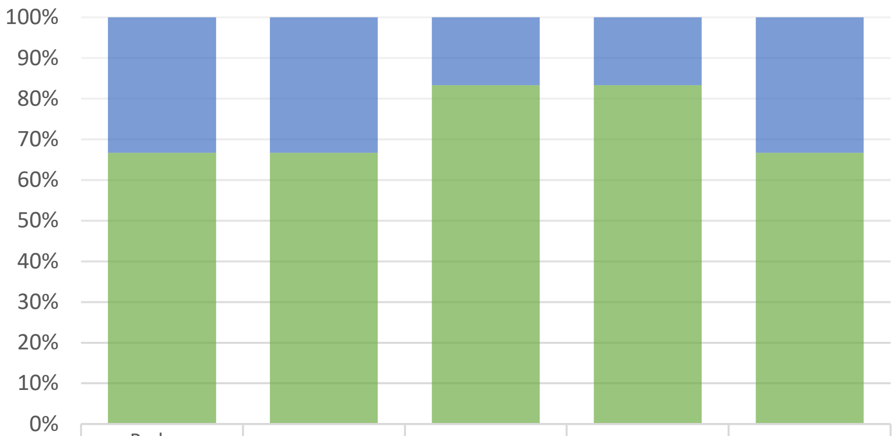
Q2.- Does your organization currently generate Renewable Energy along the road asset?



Note: Inputs of the 18 representatives have been classified by country.

Q3.- Which were the main reasons for the investment in RETs? Check all that apply?

Only if the answer to Q2 was "Yes"



	Reduce consumption of fossil fuels	Reduce GHG emissions	Electricity cost savings	Social demand	Other
No	2	2	1	1	2
Yes	4	4	5	5	4

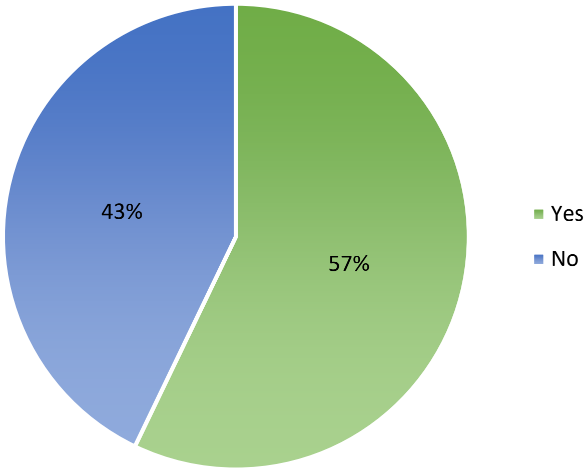
OTHER:

- To power the active devices present on our road network in an eco-sustainable way.
- Due to remote locations and lack of power supply network.
- Internal targets and learning by doing. Piloting enables us to develop the required knowledge base for third party initiatives (which are currently emerging on a large scale).

Note: Results on the base of the 5 representatives of the 5 different countries answering YES in Q2.

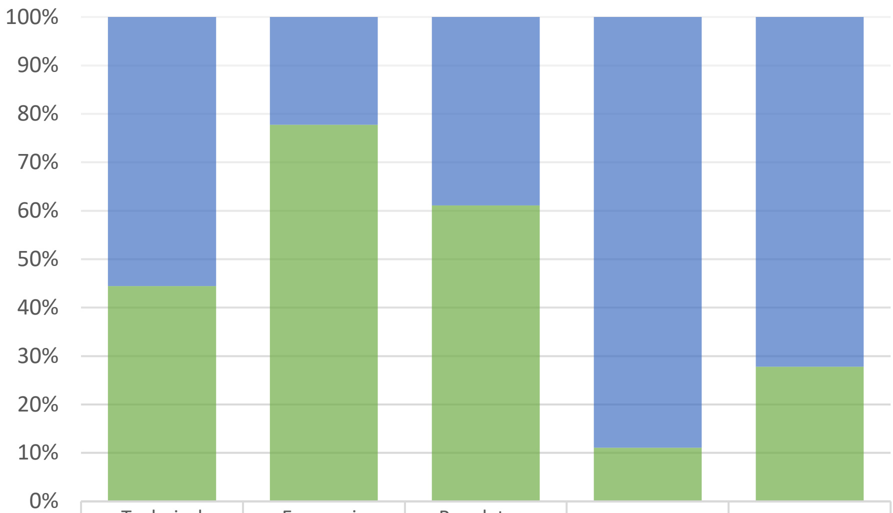
Q4.- Is your organization considering the generation of RE along the road asset?

Only if the answer to Q2 was "No"



Note: Results on the base of the 12 representatives of the 7 different countries answering NO in Q2.

Q5.- In your opinion, what is the main barrier stopping the NRAs from investing on RE technologies?



	Technical barriers	Economic barriers	Regulatory barriers	Social barriers	Other
No	10	4	7	16	13
Yes	8	14	11	2	5

Technical barriers (summary):

- How to build wind turbine along the road. It is dangeraous for cars and road is not wide enough.
- Energy storage and power distribution losses over long lengths of motorway.
- Climate and demography (long distances, low population, mountains, distributed industry).
- Local renewable solutions need high reliability which is not always so easy.
- As public services safety is at the highest priority and the availability of the services is a must.

Economic barriers (summary):

- As a NRA we have a lot of grounds available for RE, but we use a lot of energy at night (e.g. public lighting). So PV is not that interesting (only for tunnels, etc.) because everything we generate during the da has to be sold and buy more expensive electricity when we need it.
- Lack of investments due to cuts on public budgets.
- Cost of investment, need to have an subcontractor.
- Offshore wind is perceived as cost prohibitive to developers and therefore not available.
- Business cases are needed to understand the cost-benefit ratio.
- The country has plenty renewal energy available at low costs.
- Not a primary pourpose for the NRA.
- Small scale RE solutions are not always profitable and the energy we buy is 100% renewable.
- Theses RETs (e.g. solar panels) are expensive and the rate of return is relatively low.

Regulatory barriers (summary):

- It is not that easy to lease/rent/... our grounds for external parties to produce RE for their purpose. It is forbidden to generate power on someone other's ground (even with a permission from them) without a permit of the Government.
- It is forbidden (at the moment) to have an off-grid installation.
- Due to the long authorization and administrative bureaucratic process.
- Not sure if wind turbine can be built due to the proximity to the cars. Can we sell energy?
- No feed-in tariffs for public bodies.
- Planning permission and connection to national grid e.g. REFIT (Renewable Energy Feed in Tariff).
- Not a primary pourpose for the NRA.
- The current legislation does not allow the NRA to produce and sell energy, only for own use.
- No budget for such investments. Moreover, we are not allowed to sell electricity.
- Regulation prevent the generation and sale of energy back to the grid.

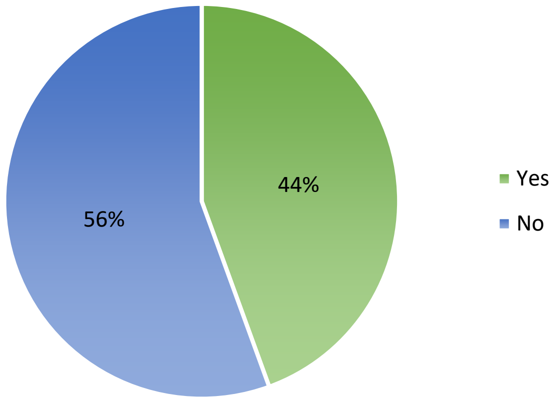
Social barriers (summary):

- Getting a permit from the city for placing wind turbines is not easy as the cities tend to follow the public opinion and a lot of citizens are pro green energy but not in their backyard.
- Reluctance from public stakeholders to wind turbines, NIMBY (Not In My Back Yard).

Other (summary):

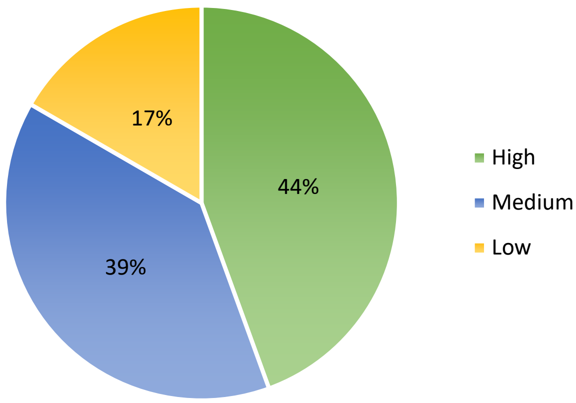
- Using RE for own use is easy. Selling it is against out objectives and regulations.
- Uncertainty in the cost-benefit rate due to lack of experience.
- Lack of awareness of available technologies.
- No clear regulations from the Authorities or Owners.

Q6.- Do you think that a decision support tool would be of help for NRAs to move forward?

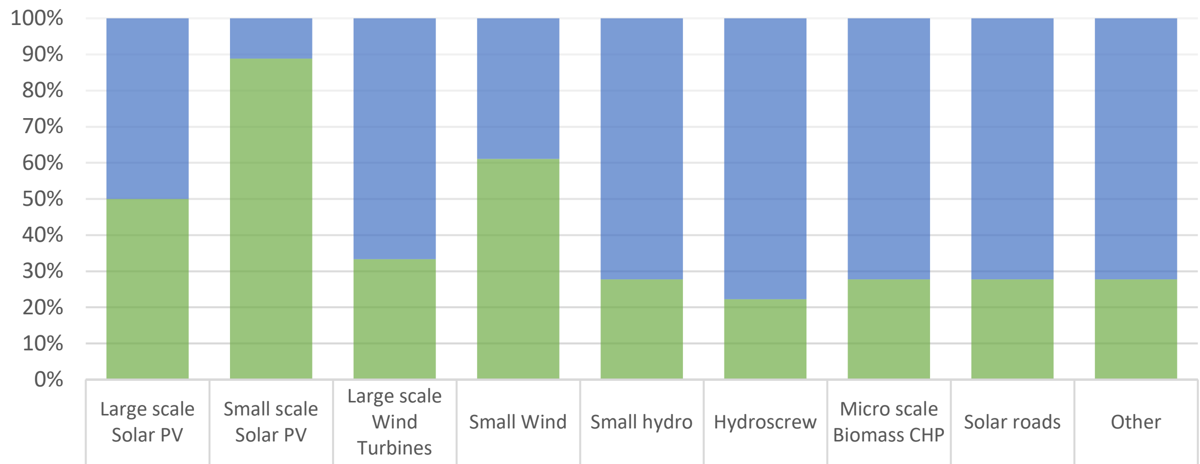


Note: Results are similar if the inputs of the 18 representatives are classified by country.

Q7.- How is, in your opinion, the social acceptance in your country of RETs within the road assets?



Q8.- Which of the following RETs would you consider for implementation? Check all that apply.

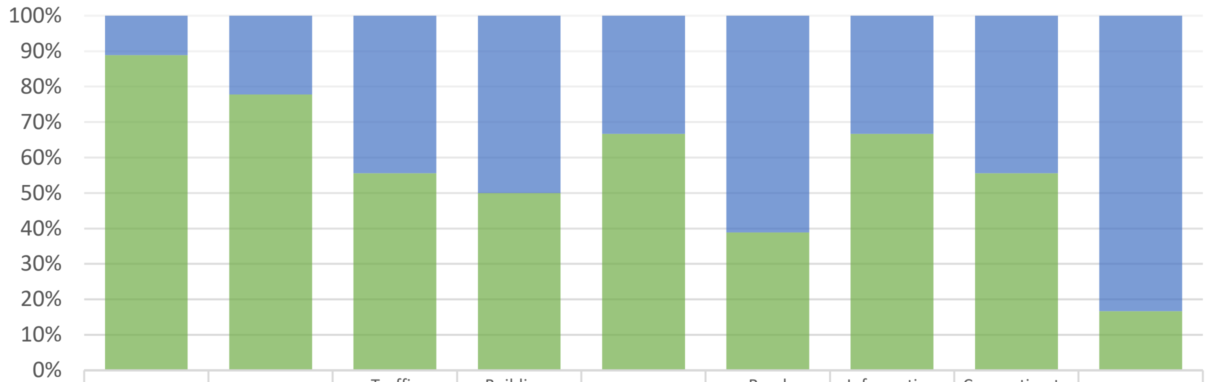


	Large scale Solar PV	Small scale Solar PV	Large scale Wind Turbines	Small Wind	Small hydro	Hydroscrew	Micro scale Biomass CHP	Solar roads	Other
No	9	2	12	7	13	14	13	13	13
Yes	9	16	6	11	5	4	5	5	5

OTHER:

- Geothermal
- Motorway acoustic panels (PV panels)
- Water mills under bridges
- Floating PV

Q9.- For which of the following energy consumers would be the RE used? Check all that apply.

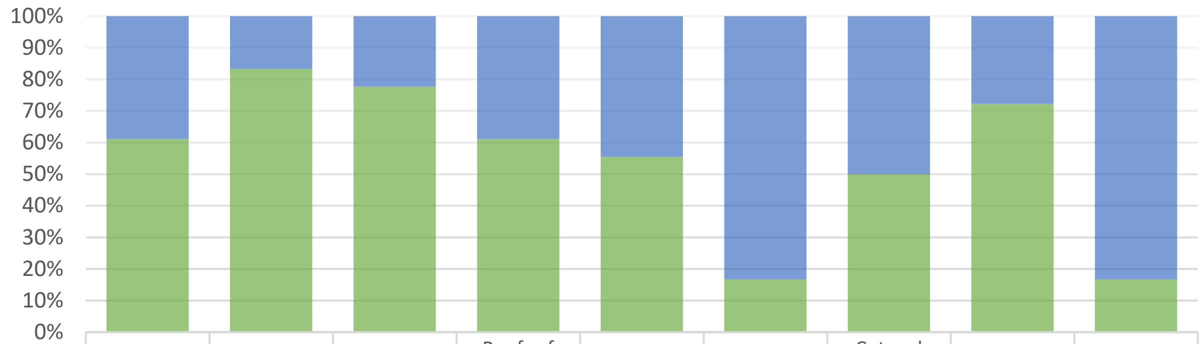


	Road lighting	Tunnel lighting	Traffic signaling	Buildings lighting	EV charging	Road electrification	Information panels	Connection to the grid	Other
No	2	4	8	9	6	11	6	8	15
Yes	16	14	10	9	12	7	12	10	3

OTHER:

- Light Rail Transport.
- Animal warning signs and communication in remote areas.
- Support of heating (in buildings).

Q10.- Which of the following road topologies would you consider for the RETs? Check all that apply.

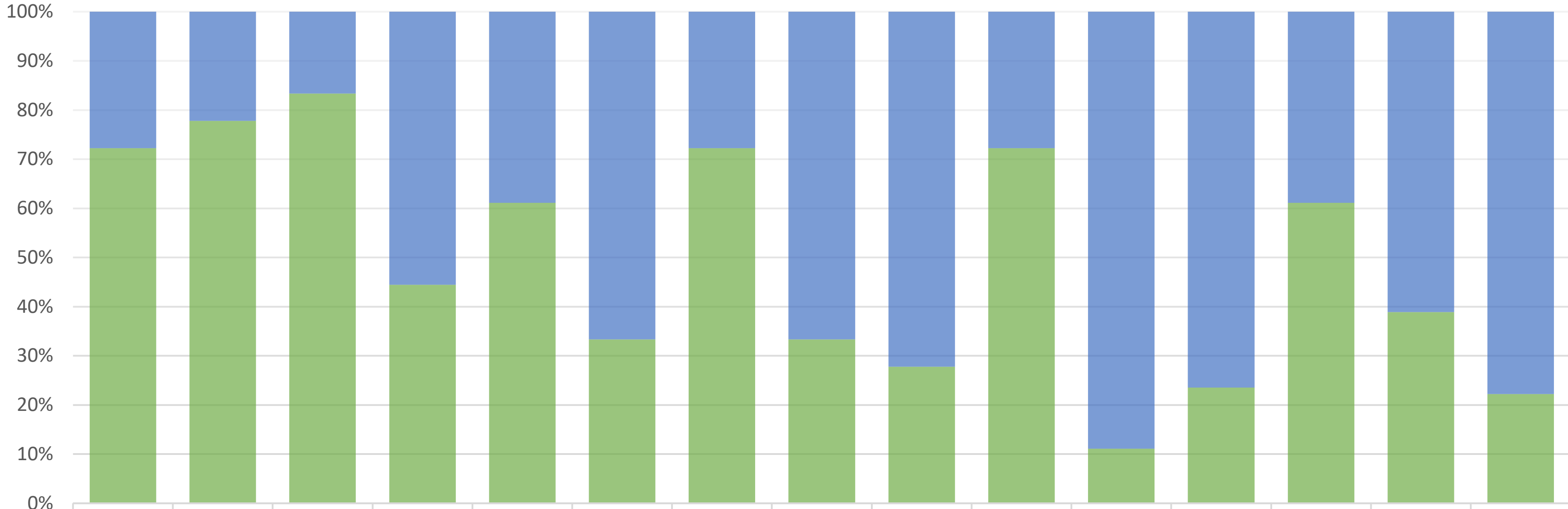


	Roadsides and slopes	Rest areas	Parking canopies	Roofs of NRAs buildings	Noise barriers	Lake, rivers or channels	Cut and cover tunnels	Signals and panels	Other
No	7	3	4	7	8	15	9	5	15
Yes	11	15	14	11	10	3	9	13	3

OTHER:

- Junction areas.
- No rivers or lakes associated with our network, would explore potential for drainage channels.
- Bike-road pavement.

Q11.- Which of the following criteria would you use for the selection of RETs? Check all that apply.

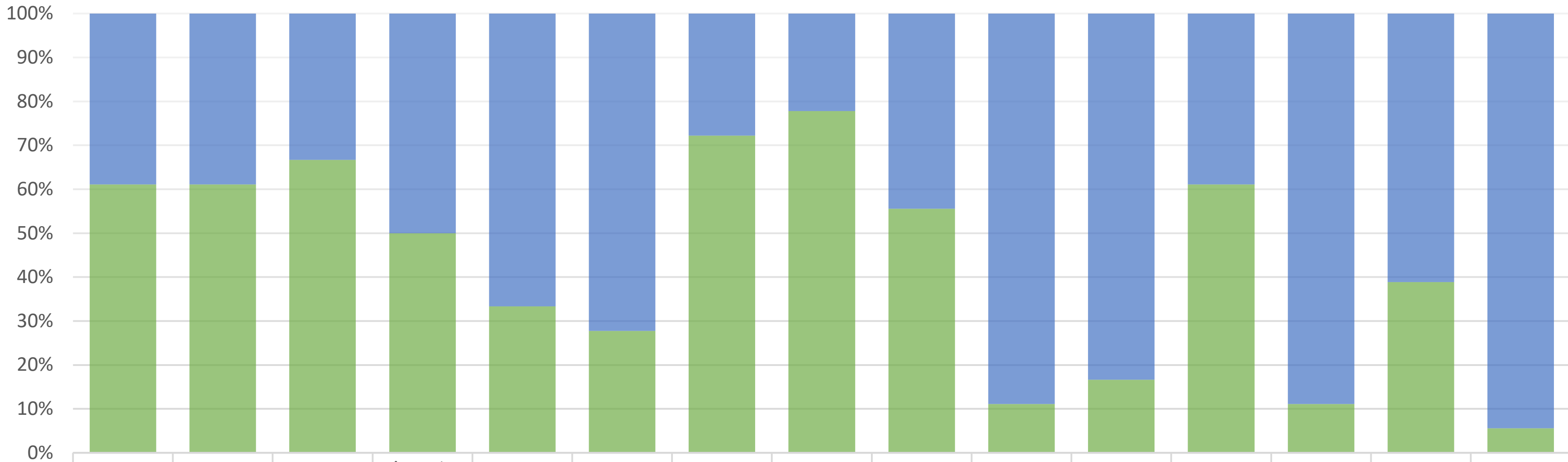


	Cost of installation	Cost of maintenance	Life cycle cost	Power output	Energy efficiency	Visual impact	Environmenta l impact	Tax aids or incentives	Ease of transp and assembly	Ease of maintenance	Proximity of supplier	Size	Durability	Social acceptance	Other
No	5	4	3	10	7	12	5	12	13	5	16	13	7	11	14
Yes	13	14	15	8	11	6	13	6	5	13	2	4	11	7	4

OTHER:

- Impact on our targets concerning RE and energy efficiency.
- Legal criteria, emc and reliability.
- We don't make investment decisions but leave these to third parties. We issue permits if the project does not affect road functionality, safety, maintenance and sometimes the environment.
- Stability of energy production.

Q12.- Which of the following criteria would you use for the location of RETs? Check all that apply.



	Availability of energy source	Proper access to the area	Distance to the road	Access to energy network	Social acceptance	Geological properties	Avoid traffic disruption	Impact on road safety	Security implications	Employment generation	Tax aids or incentives	Availabla area	Closeness to urban areas	Remoteness of the area	Other
No	7	7	6	9	12	13	5	4	8	16	15	7	16	11	17
Yes	11	11	12	9	6	5	13	14	10	2	3	11	2	7	1

OTHER:

- In our role as permit provider we focus on those issues that are within our jurisdiction. In the Project planning, we of course consider also wider issues but the decision on those issues is with the project developer or other relevant authorities (municipality/province mostly).
- Necessity of such energy source.

CURRENT EXPERIENCES (Q1-Q10)

THE NETHERLANDS 1
Current status
Use Phase
Brief description
The Solar Highways project was executed between 1 June 2014 and 30 June 2020 by Rijkswaterstaat and TNO with a subsidy from the European Commission within the LIFE + programme. In Uden, along the A50 highway, a bifacial solar noise barrier of 400 meters long and 5 meters high was constructed. The special thing about the structure is the fact that the solar cells are actually integrated in the noise barrier and have not been added to it. The vertical position also makes it possible not only to block the noise well, but also to capture a lot of light on both sides and thus generate electricity. Because the solar cells absorb light energy on both sides, optimum yields no longer depend on having a south-facing installation. The amount of energy generated is virtually independent of the direction in which the motorway runs. Optimum use is always made of both morning and afternoon sun. https://www.solarhighways.eu/en
How did you select the location and the RET?
The original location for the Solar Highways project was not suitable so a replacement location had to be found. In this particular location (A50 near Uden), accoustic measurements showed that the ground level used in the original acoustic survey carried out before constructing the A50, was too low. The actual ground level location is higher and the estimated effect of the barriers built is therefore overrated. Based on these investigations Rijkswaterstaat decided to replace the existing screen near Uden with a new 5 meter high barrier. In June 2015 shadow measurements were performed by SEAC which showed that the location is perfectly suitable for the Solar Highways project.
Where did the funding come from?
Public institution: EC subsidy and NL government funding.
Has further employment been generated through this project?
Yes, but only temporary work.
Was there a need for any kind of traffic management during the installation of the RET?
No
By whom was/is this RET designed and managed?
Designed by external organizations and managed by own personnel with average knowledge on energy generation.
Have there been safety, security or vandalism implications?
Vandalism: during the monitoring period, a few events of vandalism occurred, such as graffiti and module damages probably caused by rock throwing. However, actions were promptly taken to restore the system and no impact on the yield was found.

Have there been maintenance or cleaning implications?
Yes
Please provide any other information that might be interesting for the purpose of this survey.
The CAPEX for the Solar Highways solar noise barrier was much higher than foreseen. In all income scenarios this leads to higher O&M costs than income generated by using or selling the electricity. This leads to a negative Return in Investment and negative Net Present Value. With cost reductions for the components and efficiency improvements in the tendering and building process, costs may be able to go down to a level that will result in a positive net present value and return on investment. A further major issue was that RWS is not legally allowed to be an energy supplier. For that reason, ownership of the structure has been split into a noise part and a PV part.

THE NETHERLANDS 2
Current status
Construction Phase
Brief description
The project entails the construction of a wind farm on the beach and levvy of the MAasvlakte 2 in the Rotterdam Port area. Rijkswaterstaat has selected a contractor to design, acquire permits and build the wind farm. Rijkswaterstaat will sign a Power Purchase Agreement (PPA) with the contractor to supply the ministry of Infrastructure (I&W) with all the green power I needs to operate our assets. For more information: https://windparkmaasvlakte2.nl/
How did you select the location and the RET?
Rijkswaterstaat owns the grounds on the location and signed a collaboration agreement with other governmental organizations to select a contractor to build the windfarm.
Where did the funding come from?
Public institution: State of The Netherlands.
Has further employment been generated through this project?
Yes
Was there a need for any kind of traffic management during the installation of the RET?
Yes
By whom was/is this RET designed and managed?
N/A

Have there been safety, security or vandalism implications?
N/A
Have there been maintenance or cleaning implications?
N/A
Please provide any other information that might be interesting for the purpose of this survey.
N/A

THE NETHERLANDS 3
Current status
Design Phase
Brief description
The 'A6 Zon Lelystad Dronten' is a project to enable the contruction of a large scale solar plant along a 30km highway (A6). The project aims to generate 100MW by solar panels in 2025 -2026. Application of the energy will not be prescribed and can be decided by the future operator. The location within the 30 km of roadside and the design of the solar powerplant is still open for discussion. Ideas can be viewed on the website of the project. Decision making in this phase of the project is strongly based on the view and opinion of local inhabitants and stakeholders: https://www.a6zonlelystaddronten.nl/default.aspx
How did you select the location and the RET?
The decision the explore possibilities for the generation of renewable electricity on the roadsides of the A6 was selected by local government based on preferences from local inhabitant of the region. The inhabitants of the region favour roadsides over agricultural land and natural parks as a location for the generation of renewable energy. Solar panels are the only technological option to generate electricity as windturbines cannot stand within 70-90 meters of the highway. Furthermore, the region already fully developed the possibilities of windturbines as the province of Flevoland generates the highest amount of renewable electricity by wind turbines in NL.
Where did the funding come from?
Public institution: funded by the national government by the 'pilotprogramma hernieuwbare energie op rijksgronden' and the 'provincie Flevoland' and the local municipalities and the local electricity public network operator (Liander).
Has further employment been generated through this project?
Yes, but only temporary work.
Was there a need for any kind of traffic management during the installation of the RET?
N/A

By whom was/is this RET designed and managed?
N/A
Have there been safety, security or vandalism implications?
N/A
Have there been maintenance or cleaning implications?
N/A
Please provide any other information that might be interesting for the purpose of this survey.
N/A

THE NETHERLANDS 4
Current status
Design Phase
Brief description
The project is divided across four motorway interchanges along the highway A7. Several fields within of directly adjacent to these interchanges will be fully or partially used for solar enegy production. More information can be found here (in Dutch): https://www.energieoprijksgrond.nl/projecten/zon-langs-de-a7
How did you select the location and the RET?
The location is chosen based on general support of national and local government to make use of unused land close to main infrastructure for production of renewable energy. Several other sites in the Netherlands are currently being developed or investigated for this same reason.
Where did the funding come from?
Public institution: Ministry of Economic Affairs and Climate.
Has further employment been generated through this project?
Yes
Was there a need for any kind of traffic management during the installation of the RET?
N/A

By whom was/is this RET designed and managed?
N/A
Have there been safety, security or vandalism implications?
N/A
Have there been maintenance or cleaning implications?
N/A
Please provide any other information that might be interesting for the purpose of this survey.
N/A

THE NETHERLANDS 5
Current status
Design Phase
Brief description
The ‘Drentse Zonneroute A37’ is a project to enable the contruction of a large scale solar plant along a 42km highway (A37). The project aims to generate 200MW by solar panels in 2025 -2026. Application of the energy will not be prescribed and can be decided by the future operator. The location and design of the solar powerplant can be viewed by a 3D visualization: https://a37.ik-doe-mee.nl/map .
How did you select the location and the RET?
Location was selected by local government based on preferences from local inhabitant of the region. The inhabitants of the region favour roadsides over agricultural land and natural parks as a location for the generation of renewable energy. Solar panels are the only technological option to generate electricity as windturbines cannot stand within 70-90 meters of the highway. Furthermore, the inhabitants of the region are strongly against the development of windparks and favour solar solutions.
Where did the funding come from?
Public institution: funded by the national government by the ‘pilotprogramma hernieuwbare energie op rijksgronden’ and the ‘provincie Drenthe’ and the local municipalities and the local.
Has further employment been generated through this project?
Yes, but only temporary work.
Was there a need for any kind of traffic management during the installation of the RET?
N/A

By whom was/is this RET designed and managed?
N/A
Have there been safety, security or vandalism implications?
N/A
Have there been maintenance or cleaning implications?
N/A
Please provide any other information that might be interesting for the purpose of this survey.
N/A

ITALY
Current status
Design Phase
Brief description
Actually we are using RETs in our Smart Road project. The Smart Road infrastructure is a system conceived in a modular, independent and autonomous way. Each module extends for about 30 km and contemplates the construction of a special area, called Green Island, with the aim of producing renewable electricity, thus making it an energy-sustainable system. In this area we are going to install a small scale photovoltaic system and photovoltaic shelters for charging EV. Usually the Green Island is located in the junction areas of our highways. The RETs will be installed on the top of the Green island. You can find more information in a technical notebook in the link below: https://www.stradeanas.it/sites/default/files/pdf/Smart_Book_%28eng%29.pdf
How did you select the location and the RET?
The location was chosen in order to make maintenance activities easy and exploit as much as possible the areas of ANAS competence.
Where did the funding come from?
Public institution
Has further employment been generated through this project?
Yes
Was there a need for any kind of traffic management during the installation of the RET?
N/A

By whom was/is this RET designed and managed?
N/A
Have there been safety, security or vandalism implications?
N/A
Have there been maintenance or cleaning implications?
N/A
Please provide any other information that might be interesting for the purpose of this survey.
N/A

IRELAND
Current status
Design Phase
Brief description
Item 1 - Rooftop Solar PV Array: Proposed size 700KWp. The project is at design stage, planning application will be submitted in May 2021. Calculated to generate 600,000 KWh per annum. The PV array will be situated on the roof of the Dublin Luas depot (named Red Cow Luas depot) and will provide a source of clean energy for a considerable proportion of the depot electrical needs. Located at Red Cow Luas depot just off the M50 orbital motorway. Luas is the name of the Dublin light rail tram network. https://www.google.ie/maps/place/Red+Cow+Luas+Depot,+Naas+Rd,+Redcow,+Dublin+22/@53.3167945,-6.3704673,683m/data=!3m1!1e3!4m5!3m4!1s0x48670cada96817b7:0x900dc1c6618bafba!8m2!3d53.3156793!4d-6.3701291. Item 2 - Emergency Roadside Telephones: Emergency Roadside Telephones (ERT), are solar power phones provided on our major roads network for making calls to emergency services. They often placed in an area of special danger or where it is likely that there will only be a need to make emergency calls. There are nearly 1,400 ERTS installed on all major routes, 1.6km apart. They are manned 24 hours a days, 365 days a year from the Motorway Traffic Control Centre. Item 3 - VMS (Variable Message Sign): Variable Message Signs are used to help manage traffic and keep drivers better informed across the Irish road network. Located on various sections of the motorway network they offer information such as Real Time Journey Information, Active Traffic Management of unplanned events and incidents, Weather events, Management of planned events, Road works, Major national events and Safety campaigns. 90 VMS Installed across the network with the rollout of further VMS signs proposed. A project to provide a solar powered VMS signs was carried out in 2015 as many remote locations required expensive excavations, installations of cable ducts resulting in expensive civil works. TII (Transport Infrastructure Ireland) would benefit from renewable sources of power specifically for motorways in liu of the remote locations of equipment. For information on VMS signs, follow link for information https://traffic.tii.ie/

How did you select the location and the RET?
Item 1 - The location was selected based on opportunity e.g. large roof, located remote from residential developments, Red Cow site is a large consumer of electrical energy so energy produced on site can be consumed on site. The renewable energy could be generated on-site which is a pre-requisite by government in order to count against CO2 reduction and energy efficiency targets set by government as part of the public sector climate and energy targets for 2030. Item 2 - Emergency roadside telephones are placed on motorways in an area of special danger or where it is likely that there will only be a need to make emergency calls. With regards to the RET, the telephones are low energy consuming equipment so solar was perfect. Item 3 - VMS signs are used to help manage traffic and keep drivers better informed across the Irish road network which means remote areas or at least remote form populated areas so no readily available to the grid. Solar in this case was also a good choice in consideration of the relatively low electrical load.
Where did the funding come from?
Public institution: Item 1 - From TII, forming part of the annual budget all which would have come from government funding. Item 2 - Government funding. Item 3 - Government funding.
Has further employment been generated through this project?
Yes, but only temporary work.
Was there a need for any kind of traffic management during the installation of the RET?
N/A
By whom was/is this RET designed and managed?
N/A
Have there been safety, security or vandalism implications?
N/A
Have there been maintenance or cleaning implications?
N/A
Please provide any other information that might be interesting for the purpose of this survey.
The provision of alternative RET including reference sites utilised would be of great benefit to influence the decision making process within TII. TII also maintains all the equipment and as we are a government funded organisation, maintenance costs and the most cost effective and efficient expenditure of public money is required and monitored.

AUSTRIA
Current status
Use Phase
Brief description
https://www.asfinag.at/ueber-uns/newsroom/pressemeldungen/2021/smart-grid-klagenfurt/
How did you select the location and the RET?
Vicinty of tunnel or NRA buildings.
Where did the funding come from?
Public institution: ASFINAG - toll financed.
Has further employment been generated through this project?
No
Was there a need for any kind of traffic management during the installation of the RET?
Yes: installation phase.
By whom was/is this RET designed and managed?
Designed and managed by own personnel with good knowledge on energy generation.
Have there been safety, security or vandalism implications?
Safety: it has to be installed according to the normal safety rules.
Have there been maintenance or cleaning implications?
No
Please provide any other information that might be interesting for the purpose of this survey.
The provision of alternative RET including reference sites utilised would be of great benefit to influence the decision making process within TII. TII also maintains all the equipment and as we are a government funded organisation, maintenance costs and the most cost effective and efficient expenditure of public money is required and monitored.

UK
Current status
Design Phase
Brief description
This is a solar PV project. The aim is to prove that lightweight solar membrane can be fixed or molded to new and existing advanced digital signage (ADS), whilst assessing how much power can be generated and is this a feasible solution to fit to south facing ADS. The trial is to be conducted at the New and Renewable Energy Centre (NAREC) in Blythe using Solar Capture Technologies. It is estimated that between 155W – 220W of electricity per m2 will be generated, with battery storage included in the design. We are using a 4x5m2 sign for this project. Should this trial be successful we would assess the feasibility of rolling this out across appropriate signage on the SRN, typically south facing on the M6 and M1.
How did you select the location and the RET?
The location was chosen as the supplier (solar capture) has a relationship with the NAREC and have granted permission to use this site. Solar PV was selected as south facing large signs will have a large surface area to generate enough electricity for this to be feasible.
Where did the funding come from?
Public institution: Capital Expenditure from National Highways project management office budget.
Has further employment been generated through this project?
No
Was there a need for any kind of traffic management during the installation of the RET?
N/A
By whom was/is this RET designed and managed?
N/A
Have there been safety, security or vandalism implications?
N/A
Have there been maintenance or cleaning implications?
N/A
Please provide any other information that might be interesting for the purpose of this survey.
N/A

7 INITIAL SCREENING AND CONCLUSIONS

After the review of the renewable energy technologies (RETs) that allow the power generation along the road asset and of the road topologies considered so far by NRAs for their implementation, in this chapter an initial selection has been made based on the Technology Readiness Level (TRL) and Market Readiness Levels (MRL) of the technologies. Other criteria such as maintenance, accessibility, safety or security issues have been considered though.

Defined and first used by NASA to assess the technical progress of several of its satellite programmes, TRL is adopted in 2014 by the EU to boost the innovation in the Horizon 2020 Framework Programme. Today, the Technology Readiness Levels are indicators of the maturity of a certain technology. The nine maturity levels can be seen in Figure 103.

At the same time, these levels can be sorted out in 4 simpler phases according to Cyberwatching (2018): Idea (TRL 1-3), Prototype (TRL 4-5), Validation (TRL 6-7) and Production (TRL 8-9).

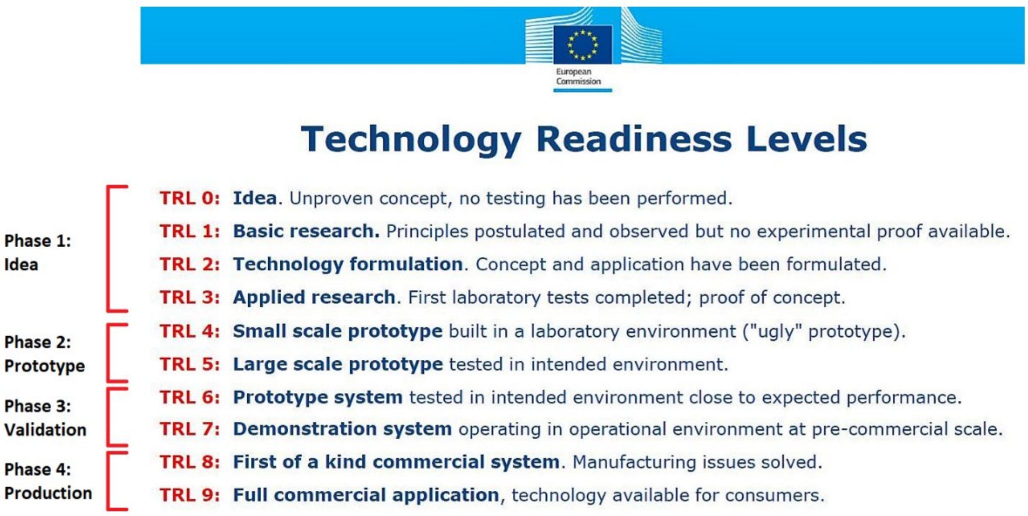


Figure 103.- TRL phases according to Cyberwatching (2018)

Market Readiness Levels (MRL) derive from the Technology Readiness Levels and measures the need of a technology in the market from the identification of an unsatisfied need to the full commercialization and scaling (CloudwatchHUB, 2016). Thus, the full development and implementation of the technology at the end of a project is not normally enough to reach the market, as other parallel activities are necessary such as business strategy, marketing, sales, etc. In this scenario, the application of the MRL methodology makes it possible the definition of the level of development of the business side of the project. The corresponding nine market readiness levels can be seen in Figure 104.

Similar to the TRL, MRL levels can be sorted out in 4 simpler phases according to Cyberwatching (2018): Idea (TRL 0-3), Testing (TRL 4-5), Traction (TRL 6-7) and Scaling (TRL 8-9).

Figure 104.- Market Readiness Levels. Source: CloudwatchHUB (2016)

A combination of TRL and MRL is sometimes interesting for the proper definition of the status of a project, technology or service. For example, a technology might be TRL 6, i.e., subjected to the validation process, but only MRL 3 as the project team has only prepared a mere ppt presentation for potential stakeholders.

Roaside renewable energy technologies have been here referred as conventional technologies that could be installed by NRAs along the road asset: solar PV, wind turbines, small hydro and micro-scale biomass power plants. In Table 6, TRL and MRL levels for the existing technologies are presented. The estimation of the TRL levels have been based on the actual definition of the methodology (level of development and maturity of the technology) and it has been made in consonance with the expertise level of the members of the University of Cantabria in charge of the description of the conventional technologies as well as with the information reported by the study *"Guidance on TRL for renewable energy technologies"*, issued by the European Commission through a framework contract intended to support its research and innovation policy in the areas of renewable energy. As for the MRL, an accurate estimation is not as straightforward as very specific information of the technologies has to be known (stakeholders following the technology, paying customers, revenues, etc.). For this reason, a simpler indirect criteria has been used: the amount of manufacturers found.

Table 6.- Technolgy and Market Readiness Levels for the conventional RETs

Technologies		TRL	MRL
Wind Turbines (Large and small generation)	Three-bladed	9	9
	Savonius	8	7
	Darrieus	8	7
	Venturi	7	2
	Small three-bladed	9	9
	Vortex	5	1
Photovoltaic (PV)	Silicon Monocrystalline	9	9
	Silicon Polycrystalline	9	9
	Silicon Amorphous	9	9
	Thin film technologies	8	6
	Multi-junction	5	2
	Organic	5	2
Mini Hydro	Pelton	9	9
	Francis	9	9
	Kaplan	9	9
	Ossberger	9	8
	Turgo	9	8
Micro-Scale Biomass	Micro-Scale CHP plants	8-9	5-6

Based on the fact that the ENROAD project is focused on high TRL technologies and medium to high MRL market status, the following conclusions could be drawn:

- Even if large-scale wind energy generation along the road asset is possible (see current experience in Belgium with the railway in chapter 5), planning, construction, maintenance and end-of-life of these devices are of course to be highly considered. As for the small-scale generation, any of the technologies here referred can be used except for Vortex, which is still under development. The Savonius turbines are actually an in-use technology, but their energy performance is much lower than the others' performance.
- All the solar PV technologies here referred can be used except for the Multi-junction and Organic technologies, both of which are still under development. As stated in chapter 2, the multi-junction technology has a very high cost and very high cost/efficiency ratio, reason for which devices with this technology have been used only in very specific situations so far.
- Large-scale hydro is obviously discarded for the purpose of the ENROAD, while all the mini hydro technologies are suitable for their use in small-scale hydro power plants, including the Ossberger and Turgo turbines, which are actually variations of the most very well-known ones.

- In the last few years there seems to be a growing interest on the development of the Micro-Scale biomass CHP plants, and even if this is a promising technology for its installation in large buildings, there is still work to do both in terms of technology and commercialization.

Built-in or non-conventional renewable energy technologies have been here considered too. In particular, a review on thermoelectric, piezoelectric and electromagnetic generation technologies has been carried out and some of the most relevant road related lab-scale or small-scale implementations have been briefly described. In this case, TRL levels have been collected from the technical literature, while the MRL levels are never higher than 2 for all the technologies when they are used in roads. In Table 7, values of TRL and MRL for the energy harvesting technologias and the solar roads (built-in PV panels) are shown.

Table 7.- Technolgy and Market Readiness Levels for the non-conventional RETs

Technology	TRL	MRL	References
Solar PV roads	8-9	2-3	Jiang et al. (2017); Wang et al. (2018); Zabihi and Saafi (2020)
Thermoelectric	3	1-2	Jiang et al. (2017); Wang et al. (2018); Zabihi and Saafi (2020)
Piezoelectric	4	1-2	Jiang et al. (2017); Wang et al. (2018); Zabihi and Saafi (2020)
Electromagnetic	3-4	1-2	Wang et al. (2018); Zabihi and Saafi (2020)

Based on the low TRL and MRL levels of the energy harvesting technologies, the following considerations could be made in the context of the ENROAD project:

- The development of solar PV roads clearly stand out from the other renewable energy harvesting technologies. However, while they are based on a very advanced technology like the PV and make use of the incident solar radiation, the other technologies harvest the energy wasted by vehicles. Therefore, the four technologies are not fully comparable.
- According to the technical literature consulted, the low TRL values of the technologies (except for the solar PV roads) are due to the very low conversion efficiencies as well as the fact the no proper large-scale experimental tests have been done.
- Low values of MRL are here referred to the application of these four technologies to the road, either by placing them on the road surface (solar PV), embedding them but keeping a part exposed (electromagnetic, when used in humps, bumps, etc.) or fully embedding them within the surface asphalt layer (thermoelectric or piezoelectric).

Apart from those coming from TRL and MRL levels, other conclusions can be drawn regarding the use of conventional and non-conventional RETs and the road topologies where they must be implemented:

- The proximity to the road of large-scale wind turbines is something to be taken into account due to potential safety issues, particularly those coming from the fall of ice from the blades and the fall of the blades themselves, but also the noise generated. For this, a certain distance to the road should be kept that mitigates that risk. In this document, a 100 m distance has been reported as resulted from a very interesting study carried out in Denmark in 2012, but further research should be done in case of installations along and close to the road.

- Photovoltaics (PV) is no doubt the most versatile technology for application along the road asset: it can be implemented in the form of PV systems (solar farms) in service areas, rest areas or in the roadside; solar canopies of parking lots; solar panels in cut slopes or noise barriers; small modules on traffic signals, etc. Cleaning and maintenance operations are of paramount importance due to the potential decrease in the energy efficiency of the installations caused by dust, bird droppings, exhaust emissions or tree leaves, among others.
- The accesibility to the energy installation is key for its proper monitoring and maintenance but on the other hand, the higher the accessibility, the higher the likelihood of vandalism and therefore, the higher maintenance costs. Thus, when the installation is accessible to the people, special care has to be taken of certain details during the design and construction phases: proper protection of electronic devices and wires, proper fastening and/or locking of the key elements, etc.
- The technical suitability of the solar roads has been proven, however, their low performance and the important maintenance issues (cell breakages and surface degradation) occurred in the scarce experiences so far makes it necessary the test of new large-scale prototypes for properly assessing those durability problems. In this sense, in the last three years a couple of new experimental solar roads, much shorter than the previous ones, have been built aimed at improving the energy yield of this technology.
- Photovoltaic Noise Barriers (PVNBs) have been proved to be a suitable technology/topology for NRAs in terms of energy efficiency, maintenance and durability. However, the newest PVNBs are only 1-2 years old so further monitoring is suggested to accurately assess the global performance of this RET. Cleaning of the PV systems in the barriers can be of great importance for ensuring an optimum energy efficiency. Nonetheless, some experiences have been here reported towards the very little impact of the cleaning operations in vertical barriers.
- The most urgent challenge for the ultimate development of the PV Noise Barriers is their financial viability. In order to offer positive Net Present Values and Return of Investments to the otherwise skeptical road managers, the income generated by using or selling the electricity must exceed the high initial investment costs and O&M costs have to be lower than.
- Low efficiencies of non-conventional RETs rule them out for their application by NRAs, at least in what large-scale projects is concerned. The green energy harvested by these technologies can on the other hand have multiple potential small-scale applications such as the powering of pavement health monitoring devices, traffic lights, information panels, infrastructure, sensors, etc.

- The suitability of the energy harvesting technologies is hindered not only by their low efficiencies but also by their very high cost as compared to the traditional power generation. Large-scale real performance tests are crucial for the proper analysis of the energy efficiency of the global system as well as for the assessment of the durability of the pavement incorporating the harvesters, the affection to the traffic and the potential harm to vehicles by devices exposed to the road surface.

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ANNEX 1: LIST OF CURRENT EXPERIENCES

(*) Two of the RETs referred were installed within the rail network, but they can be replicated in road infrastructures.
(**) Other PVNB might have been installed but they are either very old or not relevant for this study.

Location / State	Country	Year (finished)	Technology	Topology	Power Output (kW)
Krommenie	The Netherlands	2016	Integrated PV panels	Road pavement (Solar Road)	-
Haaksbergen	The Netherlands	2018	Integrated PV panels	Road pavement (Solar Road)	-
Haarlemmermeer	The Netherlands	2019	Integrated PV panels	Road pavement (Solar Road)	-
Spijkenisse	The Netherlands	2016	Integrated PV panels	Road pavement (Solar Road)	-
Blauwestad	The Netherlands	2017	Integrated PV panels	Road pavement (Solar Road)	-
Nantes Saint-Nazaire Port	France	2017	Integrated PV panels	Road pavement (Solar Road)	-
Etampes	France	2017	Integrated PV panels	Road pavement (Solar Road)	-
N401 near to Kockengen (Utrecht)	The Netherlands	2018	Integrated PV panels	Road pavement (Solar Road)	-
Tourouvre	France	2016	Integrated PV panels	Road pavement (Solar Road)	420
Georgia	USA	2016	Integrated PV panels	Road pavement (Solar Road)	-
Georgia	USA	2020	Integrated PV panels	Road pavement (Solar Road)	-
Jinan (northeastern Shandong province)	China	2018	Integrated PV panels	Road pavement (Solar Road)	-
Between Antwerp and Dutch border (along E19 highway)	Belgium	2011	PV Panels	On top of a tunnel (Solar Tunnel)	4000
Along Leuven-Liège rail line and E40 motorway	Belgium	2015	Large Scale Wind Turbines	Aside the rail network	32000
Along the highway, from Daejeon to Sejong	South Korea	2015	PV Panels	Solar Canopy (On top of bike path)	-

A13 road, Domat Ems	Switzerland	1989	PV panels	Noise barrier	100
A23 highway, Rellingen	Germany	1992	PV panels	Noise barrier	30
A1 highway, Seewalchen	Austria	1992	PV panels	Noise barrier	40
A2 highway, Giebenach	Switzerland	1995	PV panels	Noise barrier	100
A620, Saarbrücken	Germany	1995	PV panels	Noise barrier	60
A2 highway, Giebenach	Switzerland	1995	PV panels	Noise barrier	100
A9 Motorway, near Amsterdam	The Netherlands	1996	PV panels	Noise barrier	220
A96 highway, Ammersee	Germany	1996	PV panels	Noise barrier	30
Ausbrugg, near Zürich	Switzerland	1997	PV panels	Noise barrier	10
Wallisellen, near Zürich	Switzerland	1998	PV panels	Noise barrier	9.6
Fouquières-lès-Lens	France	1999	PV panels	Noise barrier	63
A6 highway, Sausenheim	Germany	1999	PV panels	Noise barrier	100
A2 highway, Gleidorf	Austria	2001	PV panels	Noise barrier	100
A1 highway, Safenwil	Switzerland	2001	PV panels	Noise barrier	80
A31 highway, Emden	Germany	2003	PV panels	Noise barrier	53
B31 highway, Freiburg	Germany	2006	PV panels	Noise barrier	365
A94 highway, Töging am Inn	Germany	2007	PV panels	Noise barrier	1000
A2 highway, Melide	Switzerland	2007	PV panels	Noise barrier	123

A22 highway, Marano d'Isera, Trento	Italy	2009	PV panels	Noise barrier	730
Oppeano, near Verona	Italy	2010	PV panels	Noise barrier	830
B57 highway, Bürstadt	Germany	2010	PV panels	Noise barrier	283
A3 highway, Aschaffenburg	Germany	2009	PV Panels	On top of a tunnel (Solar Tunnel)	2065
A92 highway, Freising (next to Munich airport)	Germany	2003	PV panels	Noise barrier	600
Along the A27 highway, near Utrecht	The Netherlands	1995	PV panels	Noise barrier	50
A52 motorway in Zumikon	Switzerland	2014	PV panels	Noise barrier	80
Along the A50 highway, near Uden	The Netherlands	2019	PV Panels	Noise barrier	240
Along the N470 road in Pijnacker-Nootdorp	The Netherlands	2017	PV panels	Noise barrier	53
Along the N470 road in Pijnacker-Nootdorp	The Netherlands	2020	PV Panels	Noise barrier	-
Along the metro line in Shanghai.	China	2007	PV panels	Noise barrier	8
Tullamarine-Calder Interchange, Melbourne	Australia	2007	PV panels	Noise barrier	24
Georgia	USA	2019-2020	PV Panels	Aside the road	1000
Oregon	USA	2008	PV Panels	Aside the road	104
Oregon	USA	2012	PV Panels	Rest area	1750
Massachusetts	USA	2015	PV panels	Aside the road	318
Massachusetts	USA	2015	PV Panels	Rest area	649
Massachusetts	USA	2015	PV Panels	Rest area	649

Massachusetts	USA	2015	PV Panels	Rest area	318
Massachusetts	USA	2015	PV Panels	Aside the road	271
Massachusetts	USA	2015	PV Panels	Rest area	567
Massachusetts	USA	2018	PV panels	Solar Canopy (Parking lot)	550
Massachusetts	USA	2017	PV panels	NRA depot	649
Massachusetts	USA	2016-2019	PV Panels	Rest area	649
Massachusetts	USA	2016-2019	PV Panels	Rest area	417
Massachusetts	USA	2016-2019	PV Panels	Rest area	649
Massachusetts	USA	2016-2019	PV Panels	Rest area	649
Maryland	USA	-	PV panels	Brige facility	22
Maryland	USA	2012	PV panels	Rooftop of Bus facility	530
Utah	USA	-	PV panels	Rooftop of NRA building	270
Utah	USA	2008	Small scale wind turbine	Rooftop of NRA building	1.8
Missouri	USA	< 2012	Small scale wind turbine	Welcome Center (outside the building)	2.4
Ohio	USA	< 2012	Small scale wind turbine	Maintenance facility	32
Texas	USA	< 2010	Small scale wind turbine	Rest area	50 kW
Texas	USA	< 2010	Small scale wind turbine	Rest area	10 kW
Utah	USA	-	PV panels	Rooftop of NRA building	-

Minnesota	USA	2019	PV panels	Solar canopy (On top deck)	274 - 548
Minnesota	USA	2020 - ?	PV Panels	Former gravel pit (NRA storage area)	Up to 3000
Minnesota	USA	-	PV panels	Rooftop of NRA building	40
Michigan	USA	-	PV panels	Rest area	-
Michigan	USA	-	PV panels	Solar Canopy (Parking lot)	96
California	USA	2011	PV panels	Rooftop of toll builiding	47.6
California	USA	2016	PV Panels	NRA facilities	1000
California	USA	2010	PV panels	Rooftop of NRA building	15

ANNEX 2: ENROAD SURVEY

Survey for the identification of Renewable Energy technologies within the NRAs assets

Name:

Organization:

Country:

Position:

Email:

Acronyms used:

- GHG: Greenhouse Gases
- NRA: National Road Administrations
- RE: Renewable Energy
- RET: Renewable Energy Technology
- TRL: Technology Readiness Level

This survey has been designed by the University of Cantabria (Spain) and reviewed by ARUP (UK) and SINTEF (Norway) within the framework of the ENROAD project (CEDR Transnational Research Programme, Call 2019).

<<< GENERAL QUESTIONS >>>

1	Does your organization have internal targets to reduce energy use and/or GHG emissions?

a) Yes

b) No

2	Does your organization currently generate RE (electricity) within/along the road asset?

a) Yes

b) No

Only if the answer to Q2 was "Yes":

3	Which were the main reasons for the investment in RETs? Check all that apply.

a) Reduce consumption of energy from fossil fuels.

b) Reduce GHG emissions.

c) Electricity cost savings.

d) Social demand.

e) Other (please specify):

Only if the answer to Q2 was "No":

4	Is your organization considering the generation of RE within/along the road asset?

a) Yes

b) No

5	In your opinion, what is the main barrier stopping the NRAs from investing on RE technologies?

a) Technical barriers (please specify):

b) Economic barriers (please specify):

c) Regulatory barriers (please specify):

d) Social barriers (please specify):

e) Other (please specify):

6	Do you think that a decision support tool would be of help for NRAs to move forward?

a) Yes (please briefly specify how):

c) No

7	How is, in your opinion, the social acceptance in your country of RETs within the road assets?

a) High

b) Medium

c) Low

8 Which of the following RETs would you consider for implementation? Check all that apply.

** Non-conventional RETs in roads: PV roads, energy harvesting using piezoelectric technology, thermoelectric energy harvesting, etc.*

a) Large scale Solar PV	d) Wind Turbines for microgeneration	g) Micro scale Biomass CHP
b) Small scale Solar PV	e) Micro/nano/pico Hydro Power	h) Solar roads (*)
c) Large scale Wind Turbines	f) Hydroscrew	i) Other:

9 For which of the following energy consumers would be the RE used? Check all that apply.

a) Road lighting	d) Official buildings lighting	g) Information panels
b) Tunnel lighting	e) EV charging	h) Connection to the grid
c) Traffic signaling	f) Road electrification	i) Other:

10 Which of the following road topologies (*) would you consider for the RETs? Check all that apply.

** This refers to spots, sites, pieces of furniture and/or equipment, buildings, infrastructures, etc., within the road asset, where the RET can be installed, mounted, fastened, implemented, coupled, etc. PV panels can be laid on top of a cut-and-cover tunnel, for example. Likewise, small solar panels can be installed in signals and panels in remote zones for their energy supply.*

a) Roadsides and slopes	d) Roofs of NRAs' buildings	g) Cut and cover tunnels
b) Rest areas	e) Noise barriers	h) Signals and panels
c) Parking canopies	f) Lake, rivers or channels	i) Other:

11 Which of the following criteria would you use for the selection of RETs? Check all that apply.

a) Cost of installation	f) Visual impact	k) Proximity of supplier
b) Cost of maintenance	g) Environmental impact	l) Size
c) Life cycle cost	h) Tax aids or incentives	m) Durability
d) Power output	i) Ease of transportation and assembly	n) Social acceptance
e) Energy efficiency	j) Ease of maintenance	o) Other:

12 Which of the following criteria would you use for the location (*) of RETs? Check all that apply.

** This refers to the geographical locations (city, town, region, area, neighbourhood, etc.) where the RET can be installed depending on the different characteristics that are sought.*

a) Availability of energy source	f) Geological properties	k) Tax aids or incentives
b) Proper access to the area	g) Avoid traffic disruption	l) Availabla area
c) Distance to the road	h) Impact on road safety	m) Closeness to urban areas
d) Access to energy network	i) Security implications	n) Remoteness of the area
e) Social acceptance	j) Employment generation	o) Other:

<<< CURRENT EXPERIENCES >>>

(*) Fill in this part of the questionnaire as many times as you need depending on the number of current experiences.

1	**What is the project status?**

a) Design phase

b) Construction phase

c) Use phase

d) End of Life

2	**Provide a brief description of the installation: RET used, energy generated, applications, location, road topology, etc. Otherwise, provide a link where this information can be found.**

3	**How did you select the location and the RET? Please, briefly explain.**

4	**Where did the funding come from?**

a) Public institution (please specify):

b) Private institution (please specify):

c) Public-private partnership (please specify):

5	Has further employment been generated through this project?
	a) Yes b) Yes, but only temporary work. b) No

Only if the answer to Q1 was "Construction phase", "Use phase" or "End of Life":

6	Was there a need for any kind of traffic management during the installation of the RET?
	a) Yes (please specify): b) No

Only if the answer to Q1 was "Use phase" or "End or Life":

7	By whom was/is this RET designed and managed?
	a) Designed and managed by own personnel with good knowledge on energy generation. b) Designed by external organizations and managed by own personnel with average knowledge on energy generation. c) Designed by external organizations and managed by own personnel with good knowledge on energy generation. d) Designed and managed by external organizations.

Only if the answer to Q1 was "Use phase phase" or "End or Life":

8	Have there been safety, security or vandalism implications? Check all that apply.
	a) Safety (please specify): b) Security (please specify): c) Vandalism (please specify): d) No

Only if the answer to Q1 was "Use phase phase" or "End or Life":

9	Have there been maintenance or cleaning implications?
	a) Yes (please specify): b) No

10	Please provide any other information that might be interesting for the purpose of this survey.