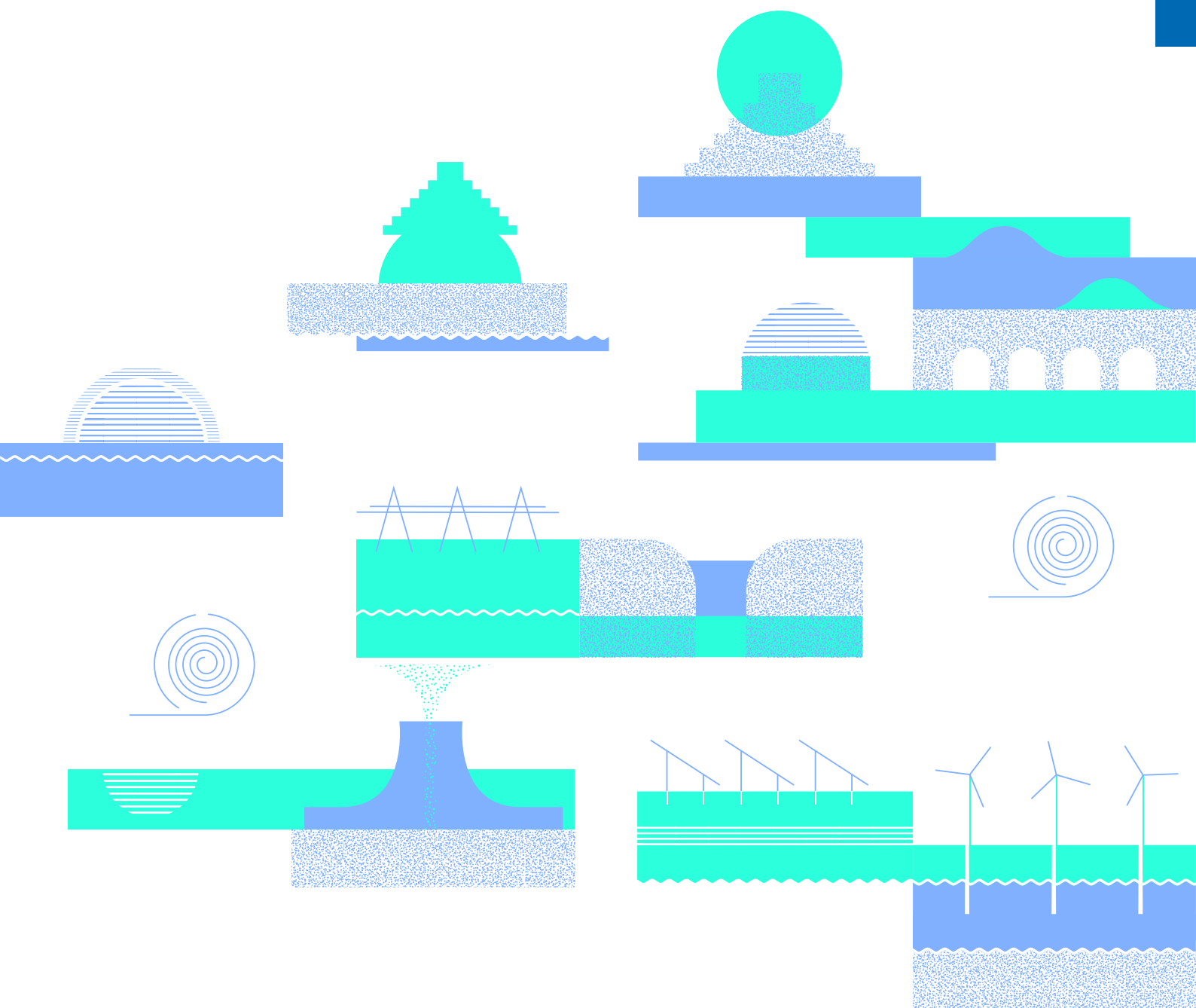


WORLD HERITAGE AND RENEWABLE ENERGY

Guidance on wind and solar energy projects
in a World Heritage context



Understanding Renewable Energy

This part of the Guidance offers an overview of wind and solar energy development and the associated transmission infrastructure development, primarily for heritage practitioners and decision-makers unfamiliar with the renewable energy field. It also discusses electrical transmission infrastructure, because wind and solar energy developments require the upgrading or development of transmission infrastructure, including power lines, substations and other facilities.

A brief overview of the main technical features and processes behind wind and solar energy and transmission infrastructure planning will enable a more effective understanding of their potential impacts on World Heritage and stimulate more efficient dialogue between stakeholders as they seek solutions. In addition, this section approaches this field with a focus on World Heritage matters, highlighting sensitive conservation issues.

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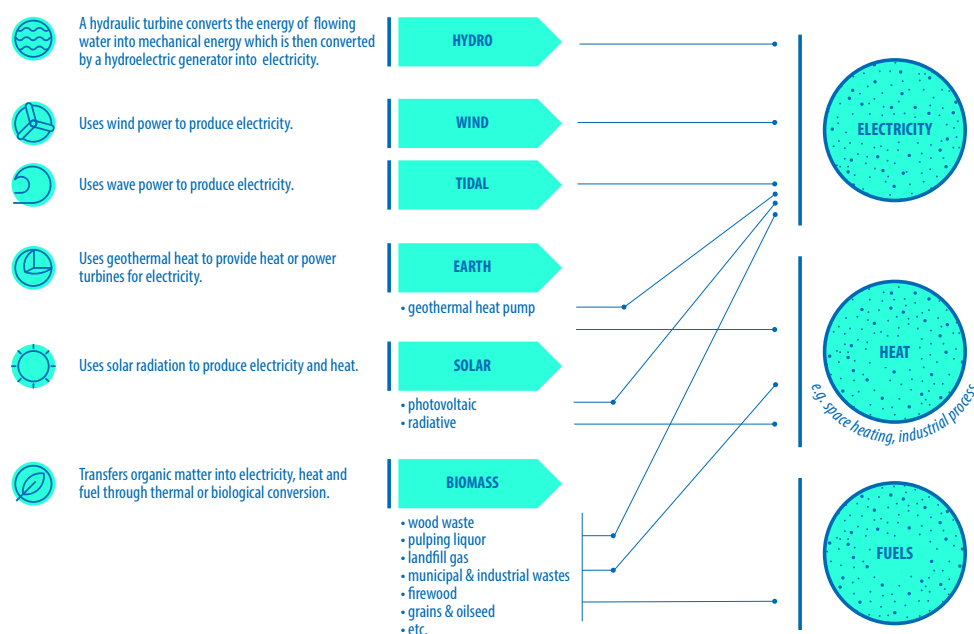
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What is renewable energy?

Renewable energy is energy that is derived from natural processes (for example, sunlight and wind) that are replenished at a higher rate than they are consumed. The sun, wind, internal heat of the Earth, water, waves and biomass (as defined in the figure below) are common sources of renewable energy. These resources are continually replenished by nature and are thus sustainable thanks to their:

- capacity not to be substantially depleted by continued use,
- minimal pollutant emissions and environmental problems,
- minimal health hazards,
- contribution to overcoming social injustice in relation to accessibility to clean sources of energy.

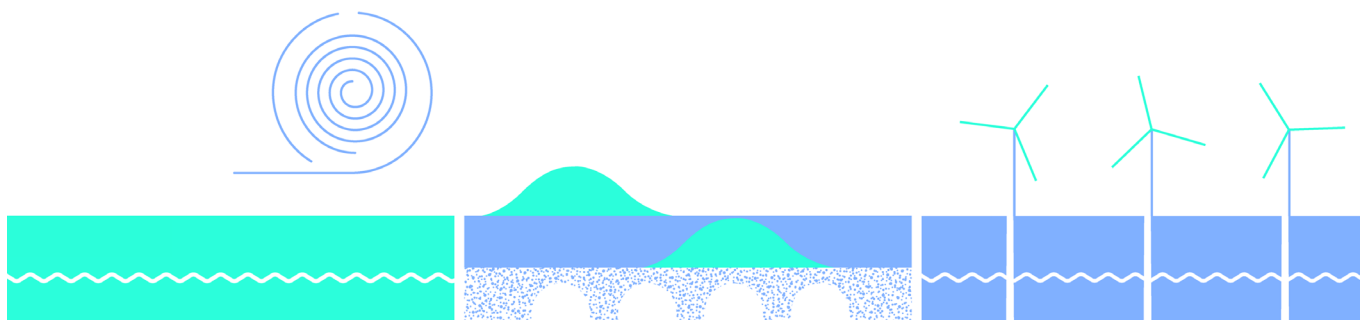


Types of renewable energy, their sources and 'primary product'.



Best practices on sustainable sourcing, responsible manufacture and responsible decommissioning or repowering

In line with the *Policy Document for the Integration of a Sustainable Development Perspective into the Processes of the World Heritage Convention*, adopted by States Parties in 2015, best practices should be followed regarding the sustainable sourcing, responsible manufacture and responsible decommissioning or repowering (including the maximal feasible recovery of scarce materials through recycling) of solar energy installations in a World Heritage property, its buffer zone or wider setting.



Scenarios for wind energy developments until 2050

To better understand the potential development of the wind energy sector in the future, a number of national and international wind energy agencies, institutions and organizations have presented scenarios for different parts of the world.

In 2019 and 2020, EU Member States submitted their [National Energy and Climate Plans \(NECPs\)](#) in which they outline how much renewable energy they plan to produce by 2030. Based on the assessment of WindEurope, wind energy capacity in the EU could reach a total of 339 GW by 2030, with 268 GW generated onshore and 71 GW offshore.

Similarly, the U.S. Department of Energy released a report titled [Wind Vision: A New Era for Wind Power in the United States](#), which shows the projected growth of the wind industry up to 2050, accompanied by a roadmap of required actions that will be updated regularly.

In [The African Continental Power Systems Masterplan](#), the African Union Development Agency–NEPAD (AUDA–NEPAD) predicts that the contribution of wind power on the continent will grow from 4% in 2023 to 23% of the energy mix in 2040, most of it being developed onshore.

The International Renewable Energy Agency (IRENA) published the report [FUTURE OF WIND: Deployment, investment, technology, grid integration and socio-economic aspects](#) (2019) with a global outlook for wind energy deployment up to 2050.

What is wind energy?

How is energy generated by the wind?

Wind energy is produced by converting the kinetic energy of moving air (wind) into electrical power using wind turbines. When wind turns the blades of a turbine, it spins a generator that produces electricity, which is then transformed into higher voltage electricity and transported through connected storage as well as distribution facilities and cable systems.

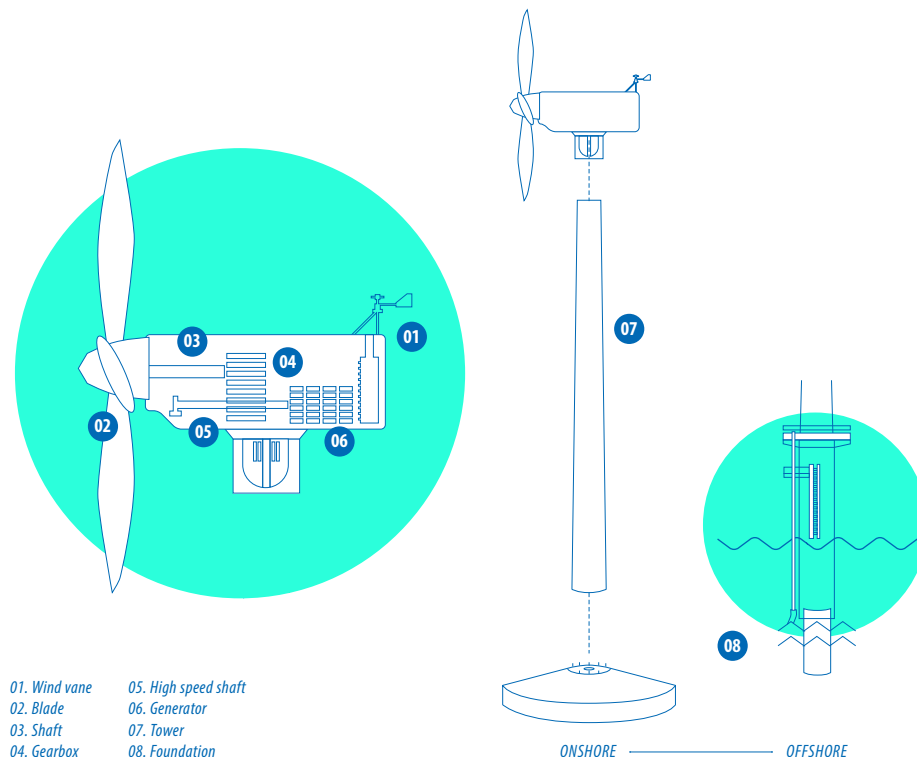
Wind energy is renewable and is regarded as a clean source of power, meaning it does not deplete natural resources or emit greenhouse gases (GHGs) during operation.

Wind energy technology is evolving rapidly. Whereas wind turbines originally required a placement on mountains and hilltops, today, thanks to technological advancements, they can be installed in more diverse settings. Wind farms can be constructed both onshore (on terrestrial areas) and offshore (on water, dominantly in seas and oceans). Taller towers and longer blades make them increasingly cost-efficient and enable a broader extension.

Components of wind energy infrastructure

Wind turbines

Wind turbines have towers made of steel and/or concrete and are crowned by a hub connected to blades of composite materials, a nacelle (casing) with the rotors, cables, a generator and a central computer system. A transformer is located at the base of the tower, connecting the turbine to the power connection and distribution grid.

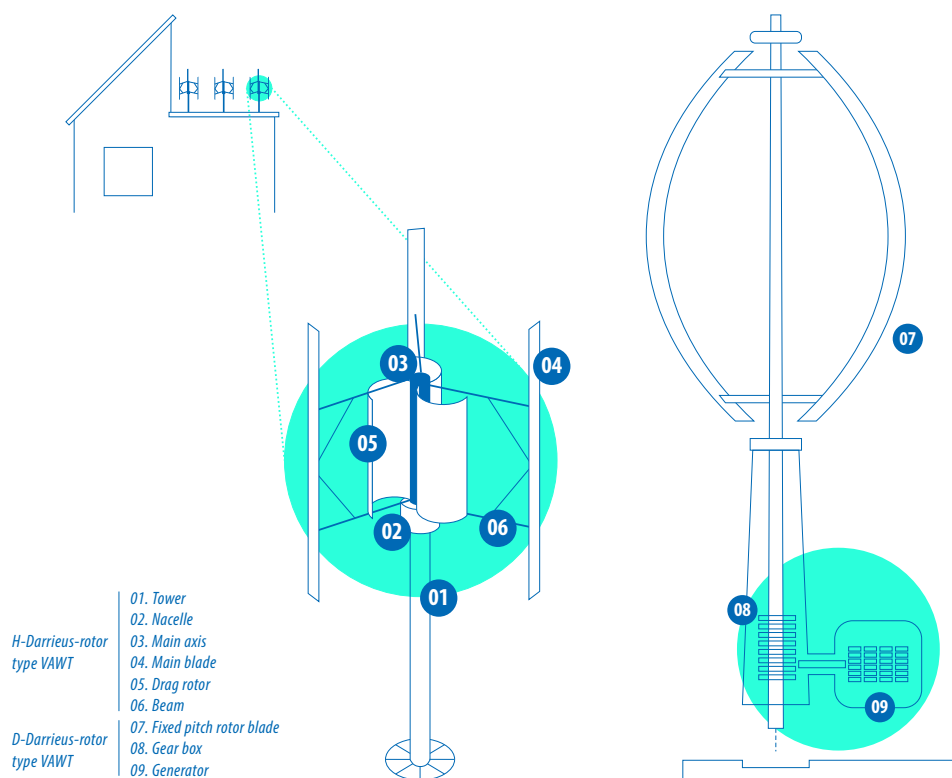


Main elements of onshore and offshore wind turbines. (source: [Wind Europe](#))

Wind turbines can be constructed on land or sea. A wide range of possible designs exists for wind turbines to adapt to different areas and conditions according to transportation requirements or the technical and commercial necessities of the developer. Turbines with larger rotor diameters capture more energy and those with higher hub heights can access higher wind speeds. They can reach a total height on land of over 300 m, although the weighted average of onshore wind turbines in Europe in 2020 was just below 120 m, with an average capacity of 8.2 MW. The average height of onshore turbines has steadily increased since 2010. In 2020, the total height of offshore wind turbines could reach up to 260 m. 5.8 MW offshore turbines with a rotor diameter of 170m have been available since 2019. (See [WindEurope's wind basics and key trends and statistics](#) as well as [IRENA's wind energy information sheet](#).)

Vertical-axis wind turbines (VAWTs) are a type of wind turbine in which the main rotor shaft is vertical. Unlike traditional horizontal turbines, VAWTs can capture wind from any direction without having to rotate. Their compact, often cylindrical or spiral design makes it possible to install them in urban or restricted areas including rooftops, the edges of buildings and open courtyards.

VAWTs are typically used for small-scale power generation, especially in environments where space is limited or wind direction varies widely. Although they generally produce less energy than horizontal turbines, they are quieter, easier to maintain and can operate well in turbulent low-wind environments. They are often used to supplement energy in residential, commercial or remote locations, often alongside solar systems. Their application in and on buildings in urban areas is growing globally.



Main elements of a vertical-axis wind turbine (VAWT).

Potential impacts of wind energy projects on World Heritage

Wind energy installations can vary substantially in size, ranging from a small wind turbine powering a microgrid to utility-scale wind farms covering many thousands of hectares. The potential impacts of wind energy in a natural and cultural World Heritage context will thus be strongly linked to scale. Impacts can vary greatly depending on the different types of attributes. It is important to remember that impacts must be assessed in relation to attributes that are already at a very early stage for each project.

In a World Heritage context, wind energy can have substantial visual and noise impacts. Wind turbines are often tall and highly visible from a distance. They can create shadow flicker during the day and may be lit at night for aviation safety. They can create infrasound, causing vibrations and noise in nearby buildings, and audible noise. They can change the way landscape morphology is perceived, significantly affect the aesthetic qualities of a place and lead to an effect of technological overload.

Choosing the site and micro-location of wind turbines requires careful consideration to mitigate such impacts, bearing in mind that viable wind resources are often localized, which may limit relocation options.

Wind power infrastructure has potential impacts on biodiversity, which may be general or very species-specific. Certain species are particularly vulnerable to potential impacts such as collisions with turbine blades and construction noise, while many may be little affected.

For terrestrial wind power, utility-scale construction typically involves clearing the vegetation and grading the surface for the wind turbine bases and surrounding access areas. Deep foundations can destroy or damage archaeological remains. Access roads may also be upgraded or created, channels dug for on-site cabling and rights of way cleared for transmission lines. For large projects, a temporary or permanent workforce might create indirect impacts through pressures on resources in the broader landscape. During operations, the regrowth of natural vegetation may be managed or prevented around turbine bases to enable easy access and maintenance. This can all result in habitat loss, degradation and fragmentation, impacting a diversity of species and reducing ecosystem conditions. Most such impacts can be avoided by siting projects only on areas with modified habitats, brownfield sites, former industrial areas and outside of the settings of World Heritage properties. Wind energy installations on already converted land offer opportunities for complementary land use through agricultural activities and/or biodiversity enhancement actions.

In the case of offshore wind power, construction can disturb and modify the seabed and lead to longer-term changes in hydrodynamics and benthic ecology, potentially resulting in habitat loss or degradation and significantly affecting sensitive seascapes. Wind farms should not be located in sensitive marine habitats. Wind-turbine towers, foundations and anti-scour structures can also provide new habitats for marine organisms, with a potential for nature-inclusive designs that can further enhance biodiversity value. (See '*Biodiversity enhancement*').

Noise or disturbance during offshore wind construction can create significant temporary impacts for certain species such as cetaceans. In some situations, collisions with maintenance vessels are also a potential risk. Scheduling construction outside sensitive periods, using bubble curtains to reduce noise transmission and pausing works in the presence of vulnerable species are examples of mitigation approaches to reduce such impacts.

Offshore wind turbines can cause collision fatalities for birds or bats (as some bat species migrate across stretches of sea), while brightly lit structures can attract some flying species and/or disrupt the movements of the latter, as well as areas of special night time scenographic value. Some seabird species may be attracted to marine structures, but others show strong displacement from offshore wind farms that can result in effective habitat loss or increase the energetic cost of movements. Large information gaps remain for the impacts of offshore wind on seabirds in many parts of the world, but where detailed studies have been undertaken, displacement is generally a more significant concern than collisions (many seabirds appear to show effective avoidance of turbine blades). Careful siting to avoid creating barriers and a turbine layout that enables corridors for movement can mitigate displacement impacts, and automated detection and shut-down systems targeted at vulnerable species have the potential to reduce collision impacts.

Both onshore and offshore wind power have life cycle impacts upstream and downstream from the installation, related to materials, construction and end-of-life disposal. (See '*Renewable energy life cycle*'). Usually, these will not directly impact a property's Outstanding Universal Value or the attributes conveying it, or other conservation values. However, in line with the *Policy Document for the Integration of a Sustainable Development Perspective into the Processes of the World Heritage Convention* adopted by States Parties in 2015, offshore wind installations within or linked to a World Heritage property should ensure that best practice is followed regarding sustainable sourcing, responsible manufacture and responsible decommissioning or repowering (including maximizing the recovery of scarce materials through recycling).

Regarding potential impacts, the following aspects of wind energy projects are relevant in a World Heritage context:

- 1) placement and design – the siting/location, layout and extension of a wind farm; the number, height, design and model of the turbines; the type of foundation and the placement and dimensions of the ancillary facilities are all factors that play a role in an assessment;
- 2) foreseen actions within each phase of the facility's life cycle – a systematic assessment should consider all phases within the life cycle of the facility and identify potential impacts on the Outstanding Universal Value of World Heritage properties for each of them. See also the relevant parts of the '*Assessing Impacts*' section.

The foundations of wind turbines bear the load transmitted from the tower and the turbine on the top, especially during the huge overturning moments of the turbine. Careful planning is therefore needed to choose the right bases for these constructions. The foundations of wind turbines can be of different types and depths depending on their location (onshore or offshore). Additionally, there are multiple criteria related to their construction needs, including the structure and height of a turbine, the wind intensity, the characteristics of the soil/seabed at the construction area and the likelihood of disasters such as earthquakes in the development area.



Types of wind-turbine foundations

For onshore wind turbines, [five common types of foundations are used today](#):

1. shallow mat extensions,
2. ribbed beam basements,
3. underneath pile foundations,
4. uplift anchors,
5. hybrid monopiles (also referred to as 'new type').

Each of these types could be round or octagonal in shape. The average diameter of the foundation ranges from 15 m to 22 m.

For offshore wind turbines, there are several types of foundations depending on the depth of the water at the site of the wind farm.

Fixed foundations can be:

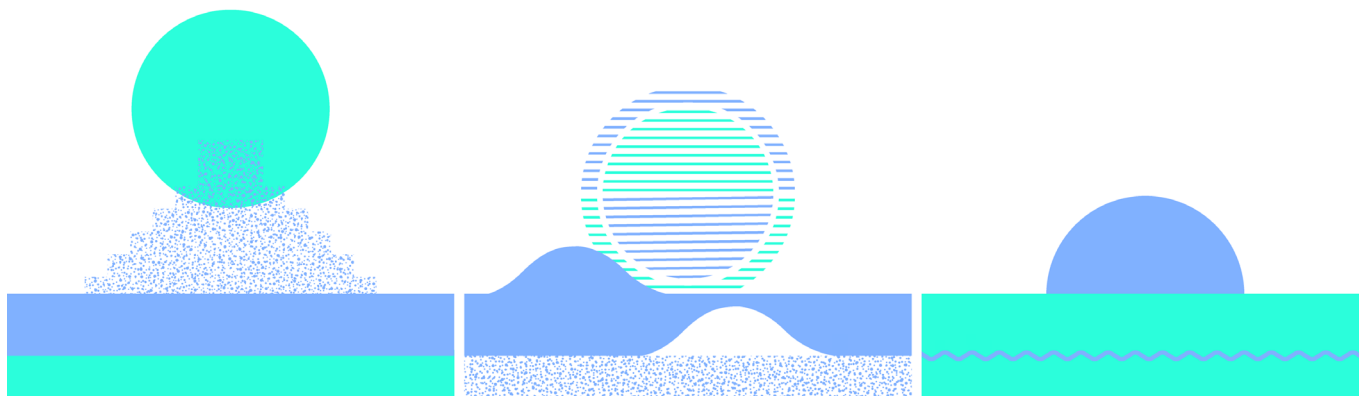
- gravity-based,
- monopile,
- tripod,
- jacket,
- pile cap,
- suction bucket.

Floating foundations can be:

- spar,
- tension-leg platforms (TLP),
- semi-submersible,
- barge,
- multi-platform.

The technology related to the construction of wind turbines is rapidly evolving. Therefore, the most up-to-date information about the characteristics, dimensions and foundation types of onshore and offshore wind turbines needs to be checked in the relevant literature, much of which is freely available on the Internet (sources: WindEurope and Canadian Wind Energy Association).

Solar energy essentials



What is solar energy?

Solar energy is the energy captured from the sun and converted into electricity (various forms of solar photovoltaics – PV) or heat (solar thermal energy and solar hot water/solar water heating) for use. Solar energy is abundant and does not produce harmful emissions of fossil fuels, making it a good alternative energy source.

Solar energy is renewable and regarded as a clean source of power, meaning it does not deplete natural resources or emit greenhouse gases (GHGs) during operation.

Solar photovoltaics (PV) are evolving rapidly and can be deployed in various forms, making this technology particularly widespread due to the scalability of solar panels. Entire fields can be covered by large-scale PV panels, while small panels can be installed on the roof or facade of an individual building.

Photovoltaic energy production

Solar photovoltaic (PV) panels capture solar energy to generate clean electricity. They achieve this through cells made of different semi-conducting materials that create

an electric field when the sun shines on them. The resulting flow of electricity can either be used directly while it is being generated, stored in batteries or other energy storage systems, or fed into the electrical grid to power homes and businesses.

Solar PV generates electricity without creating significant pollution or noise and it requires much less maintenance than other sources of renewable energy. Solar PV is also potentially compatible with other renewable energy technologies (e.g. wind energy) or activities (e.g. agriculture) and can thus enhance land use efficiency or the efficiency of appliances (e.g. to power a heat pump or an electric vehicle).

Solar PV is versatile, scalable and adaptable. This technology can be deployed in diverse settings, whether on land (ground-mounted) or on water (floating solar PV – FPV). Solar PV panels can form utility-scale installations (i.e., large enough to supply the grid with electricity) or be installed on individual roofs or integrated into building designs (e.g. solar car parks), providing distributed solar energy (i.e., enough to meet local needs).



Variations in the appearance and efficiency of solar photovoltaic (PV) technologies

Solar PV technologies are developing very fast. Solar panels no longer need to be shiny black glass-plated panels with aluminium frames. Today, it is possible to design solar PV panels to size, select a colour, control the potential reflectiveness of the surface and even have full colour images printed onto panels.

The main types of solar PV technologies include crystalline silicon (c-Si), thin-film and perovskite solar cells. Each technology has its unique characteristics, advantages and limitations.

Crystalline silicon (c-Si) solar cells

Crystalline silicon cells are the most common type of solar PV technology and are divided into two subtypes: monocrystalline and polycrystalline.

- **Appearance:**

Monocrystalline cells have a uniform, dark black surface with rounded edges, which comes from their single-crystal structure. Polycrystalline cells, on the other hand, have a speckled blue appearance due to the multiple silicon crystals used in their composition.

- **Appearance options:**

Although traditionally framed in aluminium with a glass surface, crystalline silicon panels can now be manufactured with variations in frame colour, surface texture and anti-reflective coatings. There are options for using low-glare glass and more subtly integrating panels into building structures, though the base cell colour remains more limited compared to thin-film technologies.

- **Efficiency:**

Monocrystalline cells typically achieve efficiency rates between 15% and 22%, while polycrystalline cells generally fall in the range of 13% to 16%. The higher efficiency of monocrystalline cells is due to their purer silicon composition and more effective electron flow.

- **Recyclability:**

Crystalline silicon panels are highly recyclable. Most components, including the silicon wafers, glass and aluminium frames, can be separated and processed using established recycling methods. Commercial recycling for these systems is mature and increasingly available.

Thin-film solar cells

Thin-film solar technologies involve depositing PV materials onto a base such as glass, metal or plastic. This category includes amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS).

- **Appearance:**

Amorphous silicon panels typically have a uniform dark brown or black colour. Cadmium telluride cells usually appear dark grey or matte black. CIGS panels are known for their deep black, smooth surface. All thin-film types have a more uniform appearance than crystalline silicon.

- **Appearance options:**

Thin-film cells can be manufactured on flexible or rigid substrates, making them suitable for curved surfaces or integration into roofing materials and building facades. These technologies support a broader range of appearance modifications, including variations in surface finish and colour treatments. Some versions can be integrated into glass windows or flexible fabrics for use in building-integrated photovoltaics (BIPV).

- **Efficiency:**

Amorphous silicon cells typically reach efficiency levels of around 7% to 10%. Cadmium telluride cells are generally more efficient, ranging from 9% to 11%. CIGS cells offer the highest efficiency among thin-film types, typically between 10% and 13%, with potential for further improvement.

- **Recyclability:**

The recyclability of thin-film technologies depends on the materials used. Cadmium telluride requires specialized recycling due to the presence of cadmium, a hazardous substance. CIGS and amorphous silicon are less toxic, but have fewer established recycling pathways. Research is ongoing to improve recycling methods for all thin-film technologies.

Perovskite solar cells

Perovskite solar cells are a newer technology under active development. They use materials with a perovskite crystal structure and are typically produced in thin, lightweight layers.

- **Appearance:**

Perovskite cells can be designed to be opaque or semi-transparent. Their colour and reflectivity can vary depending on their specific composition, producing a range of visual outcomes from red and brown to grey and even green.

- **Appearance options:**

These cells can be produced in custom colours and with varying degrees of transparency, making them particularly suitable for integration into windows, facades and architectural elements. Because they are made using solution-processing techniques, they can also be printed with patterns or images, offering significant aesthetic flexibility for applications such as BIPV.

- **Efficiency:**

Laboratory versions of perovskite cells have achieved efficiency levels over 25%, which is comparable to or even higher than traditional crystalline silicon. However, commercial versions are still being developed and durability remains a key area for improvement.

- **Recyclability:**

Recyclability processes for perovskite cells are still in the early stages. Due to the use of hybrid organic-inorganic materials and concerns over lead content in some formulations, efforts are ongoing to create stable and environmentally safe end-of-life strategies for this technology.

Cross-cutting options for appearance and life cycle customization

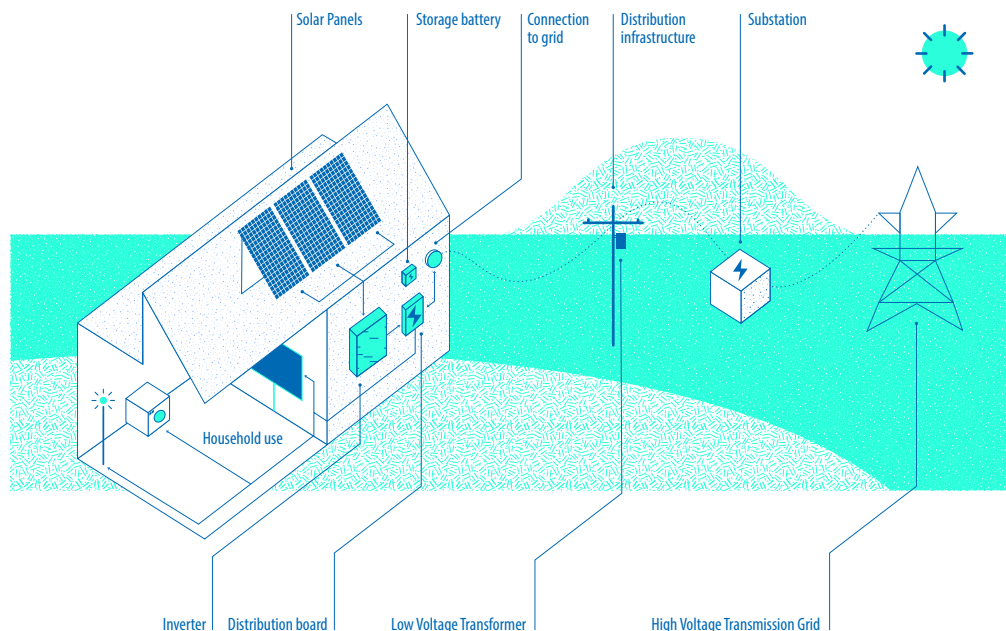
Across all solar PV technologies, various customization options are available.

- **Colour and texture control:** Solar PV modules can be manufactured with pigmented glass, matte surface coatings or printed overlays. With these modifications, the appearance of PV panels can be adjusted to better match building materials or to reduce visual contrast.
- **Reduced reflectivity:** Anti-glare coatings or etched surface treatments are available to diffuse light reflection. These features are particularly useful in minimizing glint and glare, thereby enhancing visual compatibility with the surroundings.
- **Frameless or hidden-frame designs:** Panels can be designed without visible frames or with recessed mounting systems. These options help with visual integration.

Elements of solar photovoltaic systems

Although the nature of solar PV makes it very flexible and installations may vary considerably in size and shape, they share some common elements:

- **PV panel:** this is the flat element most often associated with solar energy, which converts sunlight into electrical energy. When multiple PV panels are combined, they are often referred to as an array. A large-scale solar PV electrical production facility can be called a solar farm or a solar PV power plant.
- **The most commonly used type of solar PV panels, crystalline silicon solar PV, is composed of several elements:**
 - **solar cells or PV cells:** electronic devices that convert the energy of light into electricity (PV effect). Each cell is a small, flat square. Cells are assembled with silver strips that connect and conduct electricity. An anti-reflective layer is also applied on top of the cells to improve their efficiency.
 - **encapsulant:** the transparent layers used to hold the cells together. Made from polymeric materials such as ethylene vinyl acetate (EVA).
 - **backsheet:** the rear layer of the panel, which provides insulation and protects the PV cells from moisture, water and other external elements that could harm their performance. Made from polymeric materials such as EVA and polyesters.
 - **glass:** pane placed over the encapsulant and cells to protect them from damage.
 - **frame:** rigid outer structure, made of aluminium to support the panel's internal components and protect its edges.
 - **junction box:** small box housing the electrical connections between the cells and the external wiring system (direct current (DC) cables).
 - **inverter:** electrical device that converts the direct current (DC) generated by the PV panel into an alternating current (AC) that can be consumed. Different types of inverters are needed according to the installation: micro inverters convert the electricity generated by one panel, string inverters work with multiple panels and central inverters are used for much larger PV installations.
 - **electrical distribution system:** all the cabling, etc., which is needed to send the electricity to where it is needed.
 - **batteries or other energy storage systems:** these store electricity for later use.

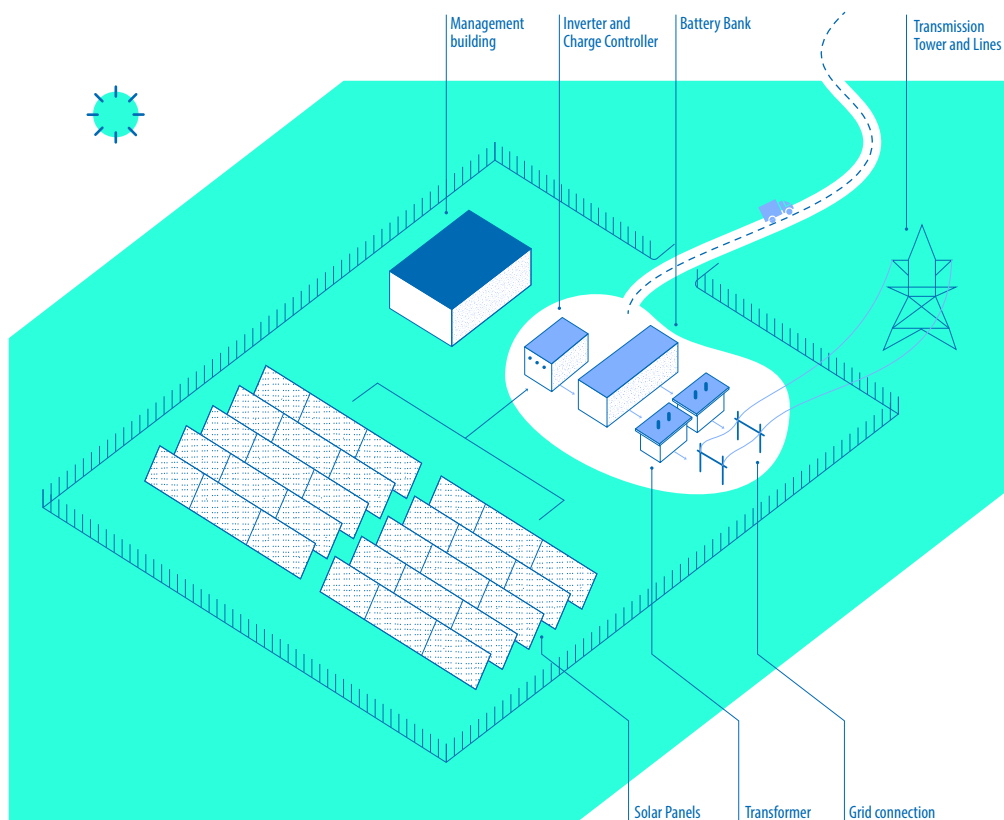


Main elements of a solar PV Installation connected to the public grid.

Solar photovoltaic systems connected to public grids

In order to replace non-renewable energy sources and meet national demand for electricity, utility-scale solar energy farms covering several hectares of land are needed. In addition to larger and more numerous photovoltaic (PV) arrays than might be installed to meet only local needs, a solar farm has additional features that are worth noting:

- **Cabling and electrical infrastructure:** these are the cables that carry electricity from the PV arrays to other elements of the solar farm. They may be buried in trenches or mounted on poles.
- **Substation:** electricity is sent to a substation before it leaves the solar farm for its voltage to be increased, ensuring a more efficient transmission over long distances. The substation then connects to the national grid. In smaller solar farms that connect to local distribution grids, the increase in voltage may be done with a transformer.
- **Transmission lines:** these are the large cables that carry the high-voltage electricity over long distances. They are usually supported by tall transmission towers.
- **Access roads:** large solar PV farms are often located in areas that require access roads to be constructed in order to facilitate ongoing operations, such as maintenance in particular.
- **Other site infrastructure** such as security fencing, potentially with lighting, will also be installed.



Main elements of a solar PV farm (power station).

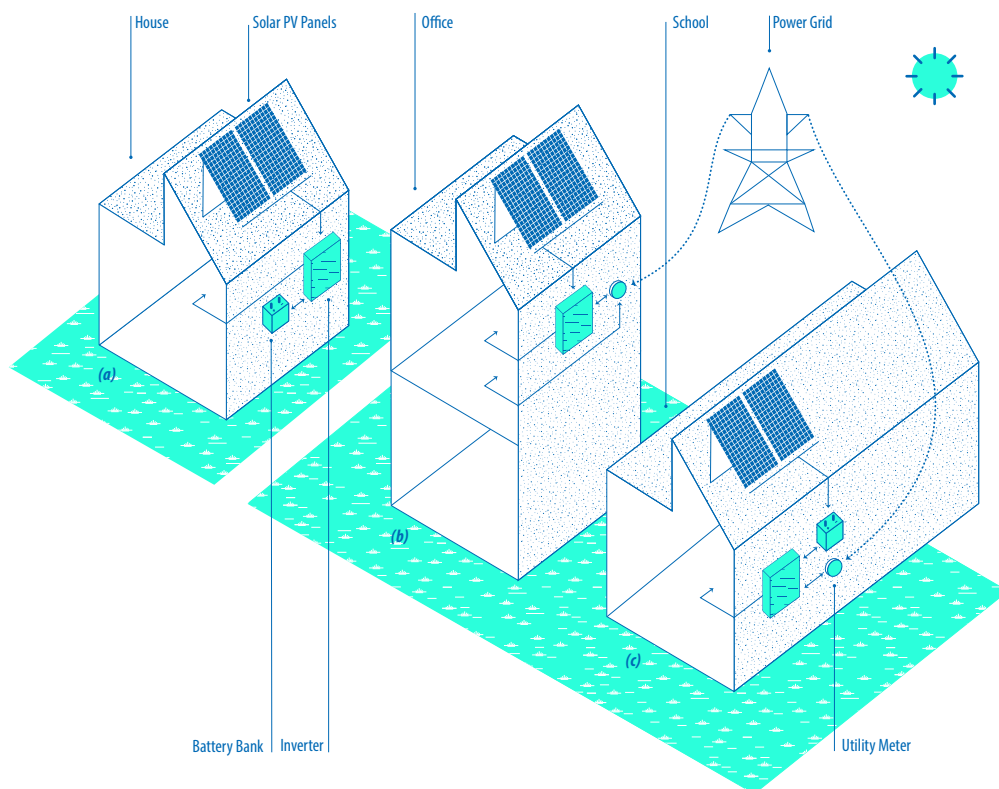
Stand-alone off-grid solar photovoltaic systems

Distributed solar energy refers to the use of solar photovoltaics (PV) to meet local energy needs. Taking a broad perspective, distributed solar energy can supplement but not replace utility-scale solar energy that supplies most national grids; however, the modular nature of solar PV means that it can be adapted to a wide range of locations, sized according to the available space. For this reason, over a third of new PV installations are on rooftops, as there are more opportunities for these smaller projects than for utility-scale solar farms that require large areas of land. Solar PV that is integrated into the built environment has the benefit of being better able to withstand climate change-related hazards such as extreme weather events than solar farms.

Distributed solar energy usually consists of a stand-alone system where the energy is either used directly or stored in batteries for later use. However, in many cases, there is the possibility for a parallel grid connection, which is used to supply energy at times when solar PV does not generate enough electricity (e.g. at night) or to send excess energy to the grid.

There are a range of options for stand-alone solar systems, including:

- panels installed over an existing roof covering: a supporting frame is anchored to the roof structure of a building and the PV array can then sit over the roof tiles or other covering. On a flat roof surface, the supporting frame is constructed so that it holds the panels in a tilted position towards the sun.
- building-integrated photovoltaic (BIPV) systems: sometimes it is possible to integrate PV panels directly into the structure of a building, replacing conventional building materials, e.g. in facades, roofs, windows or other elements (see also below the '*Building-integrated photovoltaic (BIPV) systems*').
- ground-mounted panels: when parcels of land are available or when it is not possible to mount panels on a building, PV arrays can be mounted on the ground, covering as much space as is available or desirable.



Examples of solar PV installations at single-building scale: off-grid (a), grid-connected (b), and hybrid (c).

Building-integrated photovoltaic (BIPV) systems

Building-integrated photovoltaics (BIPV) refers to the integration of solar panels into the envelope of a building, replacing conventional building elements such as roofs, walls, windows or glazed canopies when appropriate. This allows solar energy to be collected even in urban contexts where space may be limited. The energy generated by BIPV can be used by the building itself and excess energy is either stored on-site or sent back to the grid.

BIPV technology is a fast-developing field, which focuses on increasing energy production as well as developing the aesthetics of the BIPV element. Some BIPV elements are industrially developed to look as similar to traditional building elements as possible, so that they can be applied both in new buildings when required and in energy-efficient renovations.

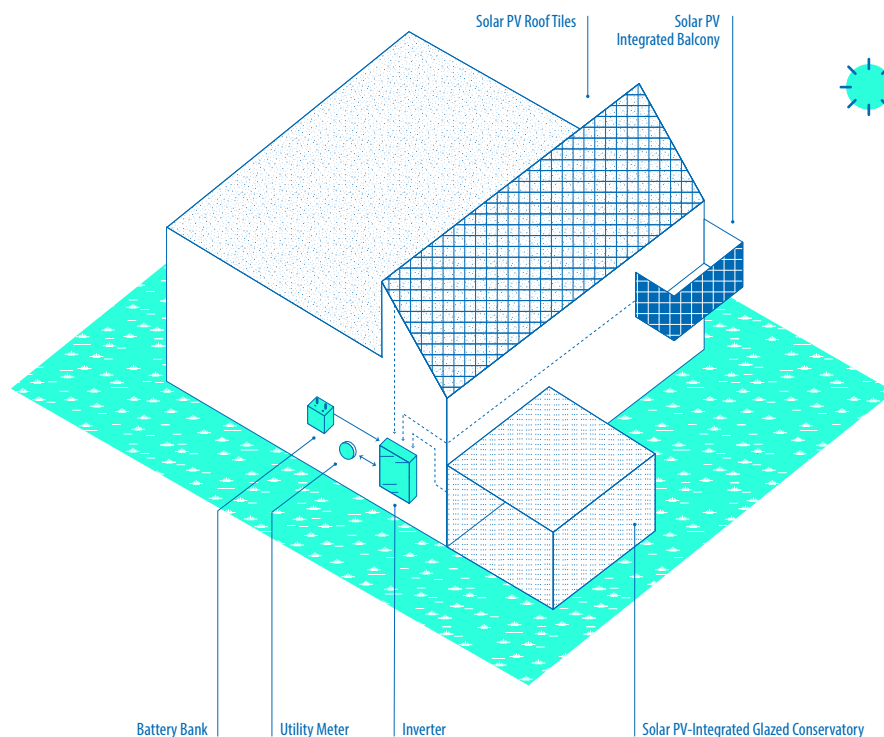
However, as BIPV is fully integrated into a building, careful attention will need to be paid to the potential loss of historical fabric. Its use should be considered only in appropriate circumstances. A full understanding of World Heritage attributes, conservation principles and heritage preservation regulations is needed to make fully informed decisions about the appropriate application of BIPV. In addition, its installation requires specialist knowledge and careful planning.

Unlike traditional solar panels, which are mounted over existing surfaces, BIPV systems are designed to merge with building features such as:

- roofs: panels can be integrated into roof coverings such as shingles, tiles, metal sheets, etc.,
- facades: panels can be integrated into exterior walls,
- windows: transparent solar panels can be used in place of windows or skylights in roofs,
- balconies: panels can be integrated into the railings surrounding balconies or terraces,
- awnings: solar canopies can be created over outdoor spaces.

BIPV can also be integrated into:

- parking structures: panels can be used as shade for car parks,
- street furniture such as light poles, bus stops, etc.



BIPV elements can be applied on different surfaces of a building.

Agrisolar photovoltaic systems (Agri PV)

The term agrivoltaics simply refers to combined PV electrical and agricultural production on the same area of land or water. Agrivoltaic systems can substantially increase land-use efficiency and help to mitigate potential conflicts between renewable energy generation and agricultural production. In some regions, agrivoltaics may also support climate change adaptation by providing shading and protection from extreme weather. Agrivoltaics could also provide an on-site energy supply for automated approaches to precision agriculture.

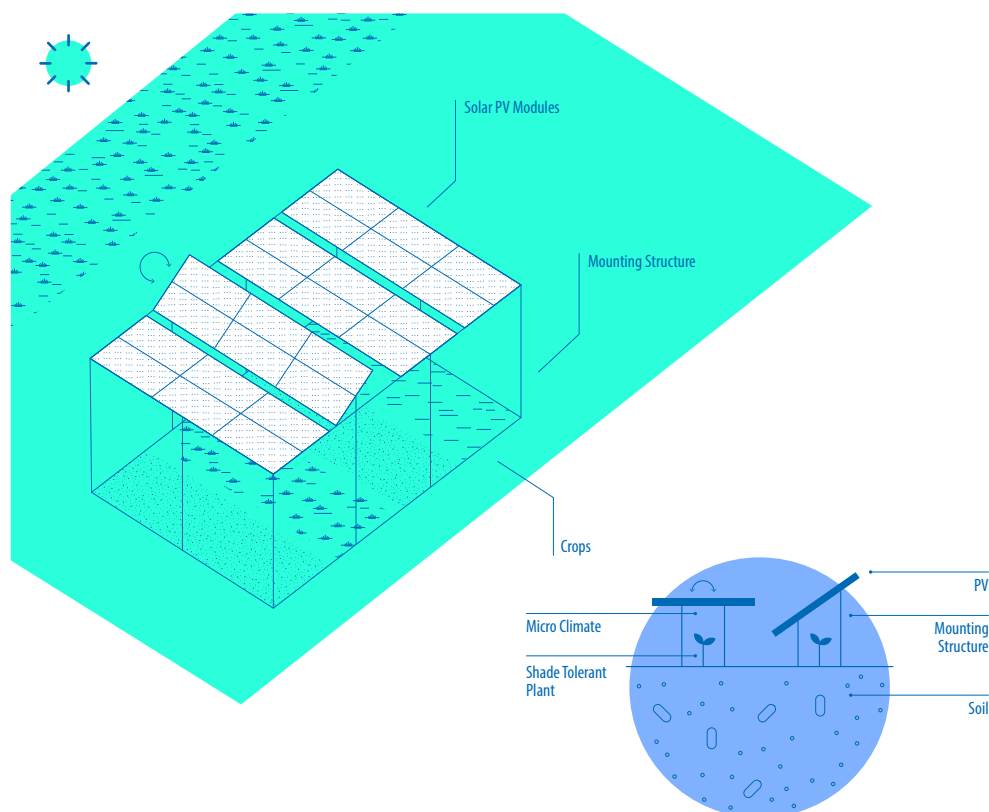
Although the concept dates back to the 1980s, agrivoltaics has only gained significant traction in the last decade or so, alongside the expansion of land-based solar farms.

Agrivoltaics can involve elevated solar panels with crops underneath, or agricultural activity in the spaces between lower-level panels. It can encompass a wide range of agricultural activities, including grassland-based livestock farming, apiculture, the arable farming of annual crops and the cultivation of perennials. Floating PV (See 'Aqua-voltaic systems (floatovoltaics)') may similarly be combined with aquaculture. Closed systems (with PV panels fitted onto greenhouses) are also a type of agrivoltaics.

The appropriate type of agrivoltaic system depends on the climatic and agricultural context. Photovoltaic panels create shade, which may limit which crops can be grown in some situations, but can also benefit crops (e.g. shade-dependent species, or crops grown in hot, dry climates) by reducing evapotranspiration, potential scorching and the air temperature. Panels can also provide soil and crops with shelter from extreme weather such as heavy rain and hail.

The careful layout of panels can help to homogenize the level of shade across a site, which is desirable for uniform plant growth.

Depending on the circumstances, suitable crops for agrivoltaic systems can include leafy greens (e.g. lettuce), fodder crops and various fruits, berries, herbs and spices. For livestock, sheep farming is a common agrivoltaic practice. An approach under trial is livestock farming combined with vertical PV arrays.



Agri-PV systems provide the opportunity to combine solar PV energy generation with agricultural production.

Aquavoltaic systems (floatovoltaics)

Floating photovoltaic systems ('floatovoltaics', also called water surface photovoltaics) are PV arrays that float on top of bodies of water. This approach is relatively new (the first functional system was installed in Japan in 2007), but expanding rapidly, and this global growth is predicted to continue.

Land for large solar PV arrays can be hard to find, especially in densely populated areas. Floating PV provides one solution to this problem, along with some technical advantages, since the cooling effect of placement in or near water can improve power generation. On the other hand, constant high humidity (especially when combined with high temperatures) can accelerate the performance attenuation (the reduction of the amount of electricity produced) of PV modules as they age, shortening their service life.

To date, the bulk of floating PV modules have been installed on large inland bodies of water, especially artificial lakes or reservoirs. Marine floating PV systems are being increasingly installed, and these can potentially be co-located with other facilities such as wind farms or aquaculture. Floating PV can also be installed on or over canals or rivers.

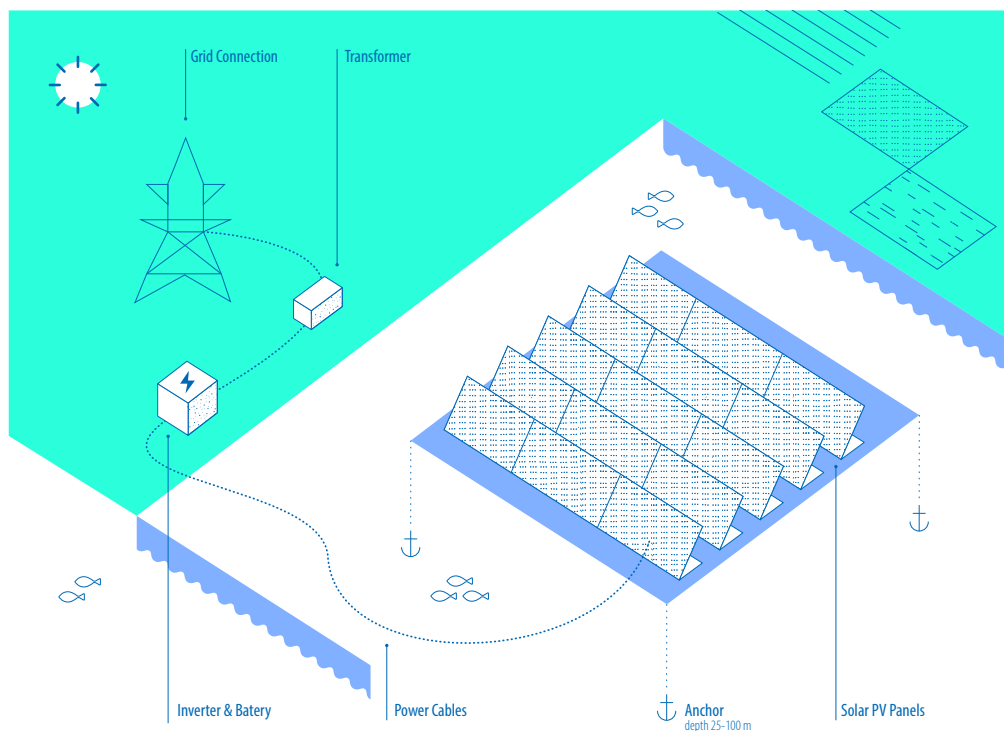
Floating PV uses a diversity of structural designs. These may include PV panels supported over the water:

- a) on trusses (e.g. across canals or channels),
- b) on piles (e.g. in shallow water),
- c) on floating buoyancy structures,
- d) on or just under the water surface, within floating frames.

Note that while (a) and (b), above, are often termed 'floatovoltaics', the installations are fixed and not actually floating.

On the sea or on large bodies of fresh water, floating PV must be able to cope with waves and water movements. Design solutions may involve panels mounted on frames above large (and relatively costly) reinforced buoyancy systems; modular floating pontoons, connected by hinges, to support the panels; or flexible thin-layer PV structures floating directly on the water.

Floating PV has a range of environmental impacts, distinct from those of terrestrial PV (and less well-studied). These will vary with the context, scale and design of floating PV installations, and can include both potentially negative and positive effects (See 'Benefits of wind and solar developments').



Main elements of a floating photovoltaic installation.



Life cycles and resource streams of solar PV technology

Solar photovoltaic (PV) technology, which is central to the clean energy transition, spans a full life cycle – from the extraction of raw materials and manufacturing to decommissioning and recycling following decades of operation. Understanding the materials used in solar PV and its environmental impact and end-of-life pathways is essential for planning sustainable solar energy systems.

Crystalline silicon (c-Si) panels (the most widely used in residential and utility-scale solar PV systems)

Efficiency:

- Monocrystalline silicon: 15%–22%
- Polycrystalline silicon: 13%–17%.

Materials and components:

- ~76% glass (protective cover)
- 8% aluminium (frame)
- 5% silicon (active layer)
- 1% copper (wiring and busbars)
- Trace amounts of silver, lead and other metals
- Plastic encapsulants (e.g. EVA) for durability and insulation.

Resource needs:

High-purity silicon requires energy-intensive processing. Scarce materials such as silver contribute to supply risks and cost pressures.

Recycling:

Crystalline silicon panels are the most recyclable type of solar PV. Aluminium and glass are routinely recovered and silicon can be reused with further refinement. The recovery of rare metals is limited but improving.

Thin-film solar panels

Efficiency:

- Amorphous silicon (a-Si): 7%–10%
- Cadmium telluride (CdTe): 9%–11%
- Copper indium gallium selenide (CIGS): 0%–13%

Used for building integration, lightweight structures and where flexibility is needed.

Materials and components:

- 88%–97% glass
- Active layers of cadmium, tellurium, indium, gallium or amorphous silicon (<1%)
- Backsheets made of plastic or metal.

Resource needs:

Although material use is lower overall, these technologies rely on rarer and, in some cases, toxic elements (e.g. cadmium in CdTe), which pose problems for the environment and supply chain.

Recycling:

Specialized recycling is needed, especially for CdTe. Recycling infrastructure is still developing, with more progress in regulated markets such as the European Union.

Perovskite solar cells**Efficiency:**

- Over 25% in laboratory settings
- Commercial efficiency still emerging

A newer, rapidly evolving technology that shows promise for low-cost, lightweight solar options.

Materials and components:

- Hybrid organic-inorganic compounds with a perovskite crystal structure
- Often include lead-based compounds
- Printed onto glass, metal or flexible plastic substrates.

Resource needs:

Lower material and energy inputs than traditional silicon. However, stability and toxicity (particularly from lead) remain under investigation.

Recycling:

Recycling is not yet commercialized. Recycling approaches are in the early research phases, with a focus on safe disposal and recovering critical materials.

morphological or aesthetic importance and disrupt important visual connections or viewsheds. There is usually some scope to mitigate such impacts, through, among other means, design, siting and technology choices, notwithstanding that solar PV panels need to be sited in an open, unshaded situation. While guidance on mitigating visual impact is mainly focused on cultural rather than natural heritage, similar approaches can be applied to natural sites.

Poorly considered solar PV has potential impacts on both biodiversity and the historical environment. The construction of terrestrial utility-scale solar typically involves clearing vegetation and grading the surface for the installation itself. Access roads may also be upgraded or created, rights of way cleared for transmission lines and, for large projects, a temporary or permanent workforce can create indirect impacts through pressures on resources in the broader landscape. Poorly planned solar PV projects can result in habitat loss, degradation or fragmentation, impacting a diversity of species and reducing ecosystem conditions. In addition, such projects, which, during construction, include digging out foundations and trenches for cabling and hardening the surface, etc., may damage or destroy archaeological remains. These potential effects underscore the importance of site-specific environmental and cultural heritage impact assessments. (See also the 'Assessing Impacts' section.)

Installing solar PV on historic buildings can result in the loss of historical fabric, for instance by replacing historical roofing, cutting through historically significant walls and floors and remodelling interiors to accommodate ancillary infrastructure such as inverters. This can lead to a loss of material authenticity and integrity, while also affecting aesthetic qualities. Larger scale solar PV installations could impact property values and lead to the gradual or sudden departure of a community associated with a heritage place.

During operations, the regrowth of natural vegetation around solar PV farms may be managed or prevented to enable easy access and maintenance. For some species, behavioural displacement (whereby animals are reluctant to forage, rest or nest within the solar farm) results in the effective loss of animals' habitat. Most such impacts can be avoided by siting projects only in areas with modified habitats (or artificial bodies of water, in the case of floating solar PV) or outside of sensitive cultural landscapes or urban environments, although, even then, the overdevelopment of a larger environment might change the experience of a cultural heritage place in its context to such an extent that it affects the setting of that heritage place. Solar farms can be designed to allow for grazing and the restoration of native vegetation and pollinator habitats, creating multi-functional landscapes that support both energy and conservation goals.

Potential impacts of solar photovoltaic systems in World Heritage

Solar photovoltaics (PV) is a highly scalable form of renewable energy. Installations can range in size from a postcard-sized panel powering a wildlife camera trap to installations on roofs to solar farms that spread over thousands of hectares. The potential impacts of solar PV in a World Heritage context will thus be strongly linked to scale, but the technology can also offer opportunities for advancing sustainability objectives when aligned with the maintenance of the Outstanding Universal Value of a World Heritage property.

By definition, and depending on siting and orientation, glint and glare from solar PV can have a strong visual impact. Even at a small scale, poorly sited solar panels could potentially impact Outstanding Universal Value related to a property's exceptional natural beauty and

Solar PV projects on already converted land offer opportunities for complementary land-use through agrivoltaics and/or biodiversity enhancement actions (See '*Benefits of wind and solar developments*' and '*Potential impacts of solar energy projects on the Outstanding Universal Value of World Heritage properties*'). Solar PV farms may often be sited in arid areas with limited vegetation and largely unmodified habitats. Impacts in such locations can be minimized by careful micro-siting to avoid features important for biodiversity (such as active burrows, drainage lines that provide shelter, nest sites and scattered woody vegetation) and the reduction of surface grading as far as possible.

Considering appropriate sites can also help to steer clear of sacred or sensitive cultural areas and avoid disrupting traditional land uses and interacting with archaeological/historical remains. By taking up large areas of land, and potentially through fencing, solar PV can potentially create barriers to animal movement and to plant and animal dispersal, and even traditional cultural routes across the landscape. This reduces landscape connectivity and could diminish gene flow, disrupt metapopulation dynamics and displace migratory behaviour (especially for large mammal species). Such impacts could be cumulative at the landscape level across multiple solar farms. They could potentially affect the attributes conveying a property's Outstanding Universal Value or other conservation values. Examples could be a threatened migratory mammal that spends part of its life cycle in the property, or an outstanding example of an ecosystem that has ecological links to other sites at landscape level. Barrier impacts can be mitigated by avoiding natural habitats through site selection, implementing a spatial design and management system that maintains and/or restores corridors for movement, and ensuring any fencing is permeable to vulnerable wildlife.

The shade created by solar PV panels modifies natural micro-climatic conditions, with impacts that may be negative or positive depending on the context and species. In hot, arid areas especially, and for floating solar PV in bodies of water, additional shade may benefit certain species or create opportunities for biodiversity enhancement. Minimizing the potential negative impacts of shading in natural habitats requires careful ecological study and the careful consideration of micro-siting and the height and density of solar PV panels.

Solar PV installations may have other direct impacts on some wildlife. Bird and bat fatalities have been recorded due to collisions with project or associated infrastructure, including panels, supports, substations, transmission lines and fencing. Collisions with service vehicles are another potential source of fatalities. Aquatic insect species may

be maladaptively attracted to polarized light from panels. For at-risk species, a number of minimization measures are possible to reduce potential collisions with transmission lines, night-lit structures, fences or vehicles. Fatalities also need to be monitored to inform adaptive management. However (contrary to wind energy), there is little evidence to date that direct fatalities from solar PV could be significant for any species at population level.

Other operational impacts of solar PV are often relatively minor. Where water is used to clean panels in water-stressed areas, there is a potential for increased pressure on water resources that could have ecological consequences and may affect the use of traditional water systems such as wells or irrigation. A number of dry panel-cleaning methods are already available, and this is an area of active research. Chemicals used for cleaning or herbicides applied to control vegetation may create runoff pollution or spray drift, which can be mitigated through non-toxic substitutes, alternative management techniques and/or careful abatement.

On smaller-scale installations, solar PV panels can compromise the structural integrity of historic buildings that were not designed for the additional weight. Installation and the associated cabling can cause direct damage to historical fabric. If sited inappropriately, they can also alter the character of the building or urban landscape. Panels installed on roofs can also risk disturbing sensitive protected species such as bats. When BIPV is considered for a historic building, the historical, aesthetic and structural characteristics of the elements that would be replaced by the solar PV panels must be carefully assessed.

Solar PV has potential life cycle impacts upstream and downstream from the installation, related to materials, construction and end-of-life disposal (See also below in '*Renewable energy life cycle*'). Usually, these will not directly impact a property's Outstanding Universal Value, the attributes conveying it or other conservation values.

Cumulative impacts are of particular concern in relation to solar PV projects. It is common to find multiple solar PV farms planned within a given area and the associated infrastructure (e.g. transmission lines, access roads) must also be taken into consideration when assessing impact, even when the projects are undertaken separately. With distributed solar energy, there can be significant cumulative impacts of solar PV panels installed on or around multiple buildings within a landscape or urban environment. In all cases, the overall potential impact of such projects on World Heritage needs to be understood when decisions are made.

Solar hot water/solar water heating

Solar hot water systems use the sun's energy to heat water for residential, commercial or industrial use. By utilizing renewable solar energy, these systems significantly reduce dependence on fossil fuels and bring down utility bills.

How solar hot water works

Solar hot water systems generally work by collecting solar radiation through solar thermal collectors, which then transfer the heat to a fluid that circulates through the system. The heated fluid is then used to warm water stored in an insulated tank, making it available for various applications such as domestic hot water, space heating and industrial processes.

- Residential hot water supply: Provides hot water for bathing, cooking and cleaning in a home.
- Space heating: Supports radiant floor heating or air heating systems in buildings.
- Swimming pool heating: Warms pool water.
- Industrial processes: Heats water for manufacturing, food processing and other commercial applications.
- Agricultural uses: Provides hot water for dairy farming, greenhouses and irrigation systems.

Solar hot water systems consist of the following components:

Solar collectors

- Flat-plate collectors: Insulated boxes with a dark absorber plate under a glass cover.
- Evacuated tube collectors: Glass tubes that improve efficiency by reducing heat loss.

Heat transfer fluid

- A liquid (often water or a water-glycol mixture) that circulates through the system.

Storage tank

- A well-insulated tank that stores the heated water until needed.

Heat exchanger

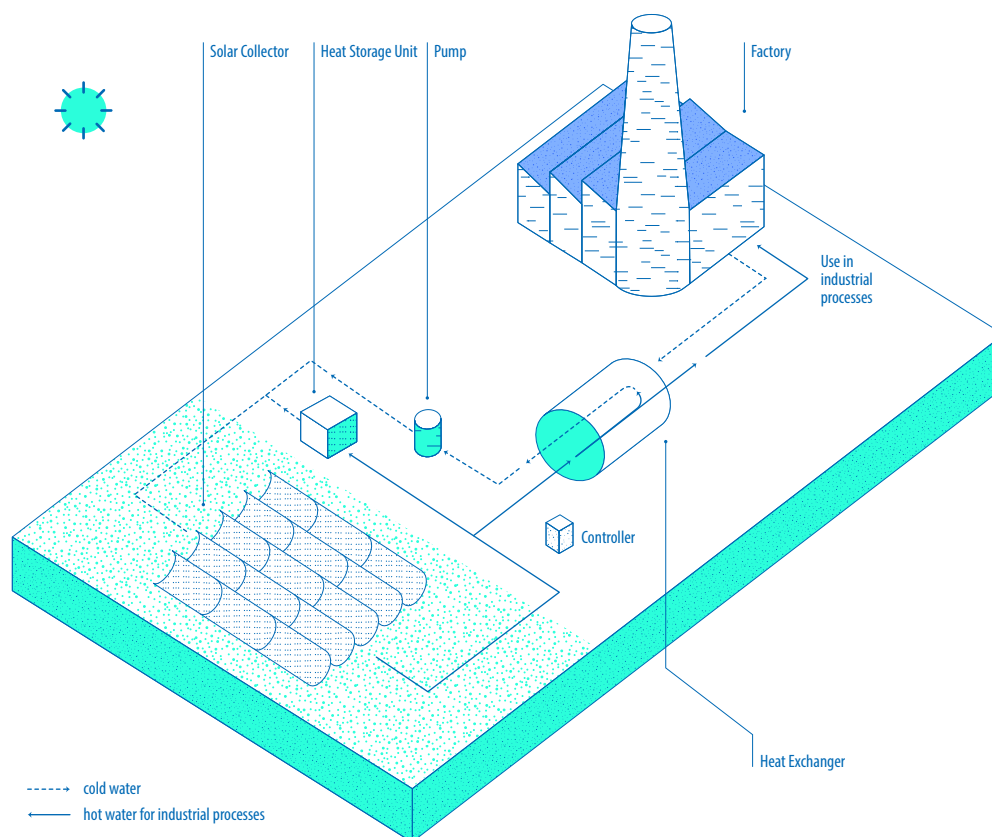
- Transfers heat from the collector fluid to the potable water supply.

Circulation pump (active systems only)

- Pumps the heat transfer fluid between the collectors and storage tank.

Controller and sensors

- Monitors temperature differences and optimizes energy collection.



Main elements of a solar hot water system on an industrial scale.

Backup heater

- An auxiliary heater (electric or gas-powered) for backup heating. If electric, this is often located in the storage tank.

Piping for solar hot water systems

- Piping is a crucial component in a solar hot water system, as it connects the solar collector to the storage tank and the end-use system. Common piping materials are copper cross-linked polyethylene (PEX), stainless steel and chlorinated polyvinyl chloride (CPVC).

Residential solar hot water systems

Solar hot water systems can be installed on the roofs of residential buildings, or adjacent to buildings, to harness sunlight for domestic water heating. The installation process begins with a site assessment to determine the roof's orientation, tilt and structural integrity, or to locate a suitable location on the ground. For roof-based installations, mounting frames are fixed to the roof, often using brackets that attach to rafters to ensure stability, or onto flat concrete roofs. Collectors are then secured to the frames. Piping connects the collectors to a storage tank, which can be mounted as part of the collector on the roof (thermosyphon systems), below in the building or on the ground (pumping systems). In pumping systems, a controller and circulation pump move water between the tank and collectors.

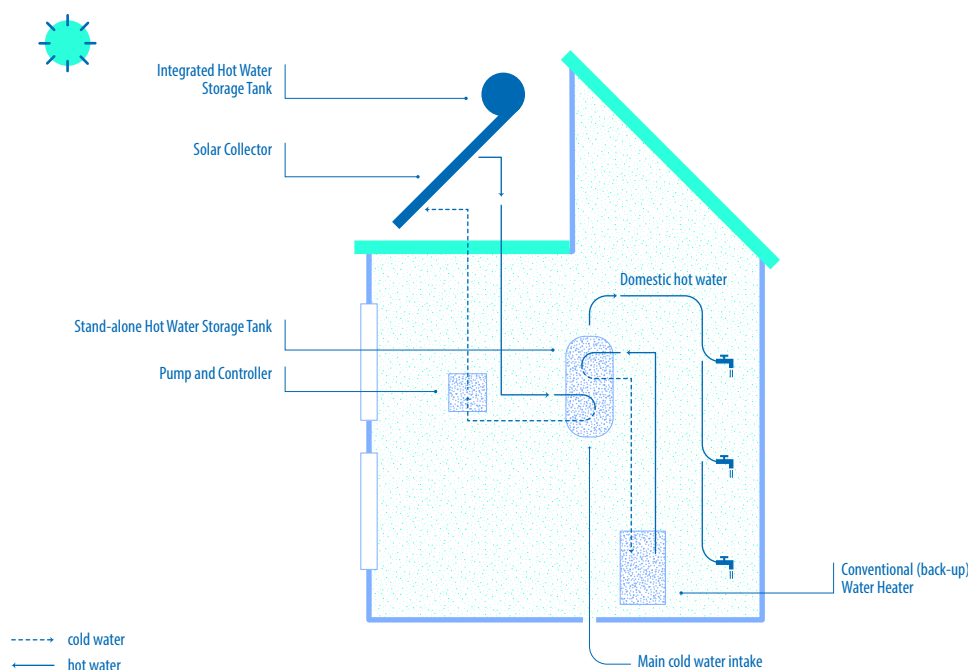
The system is then connected to the home's plumbing and, in some cases, a backup electric or gas booster is added for periods of low sunlight.

Building permit requirements vary globally. In many countries, permits are often required, particularly if the system affects plumbing, electrical systems or roof structure. However, some regions may waive permit requirements for small-scale or standard installations. Local regulations should always be checked before installation.

Potential impacts of solar hot water in World Heritage

Like solar PV, solar hot water is a highly scalable technology and potential impacts will depend on scale. At present, the great majority of global installed capacity is at a relatively small scale, on or adjacent to buildings and for domestic and residential use. Large-scale solar hot water, for use by industry and/or district heating, has been widely developed in only a few countries to date. However, it is likely that large-scale installations will become much more widespread in the future.

Little is documented about the potential environmental impacts of solar hot water. However, although it uses a different physical process, the potential impacts of solar hot water in relation to World Heritage properties are likely to be very similar to those of solar PV. Refer to the section on potential solar energy impacts (See '*Potential impacts of solar energy projects on the Outstanding Universal Value of World Heritage properties*') for details. Some differences in detail are that, compared to solar PV, solar hot water systems are less likely to result in visual glint or glare and have less demanding cleaning requirements for the collectors (so use less water during their operation, in wet cleaning systems).



Main elements of a solar hot water system typically installed on residential buildings.

Decision-making regarding the appropriateness of solar hot water systems on historic buildings should consider their visual impact as well as the structural capacity of the building. Solar hot water systems often require the installation of additional water and electrical conduiting. The location and installation method of these reticulation lines should be carefully considered with regard to the impact on authentic building fabric, visual impact and reversibility.

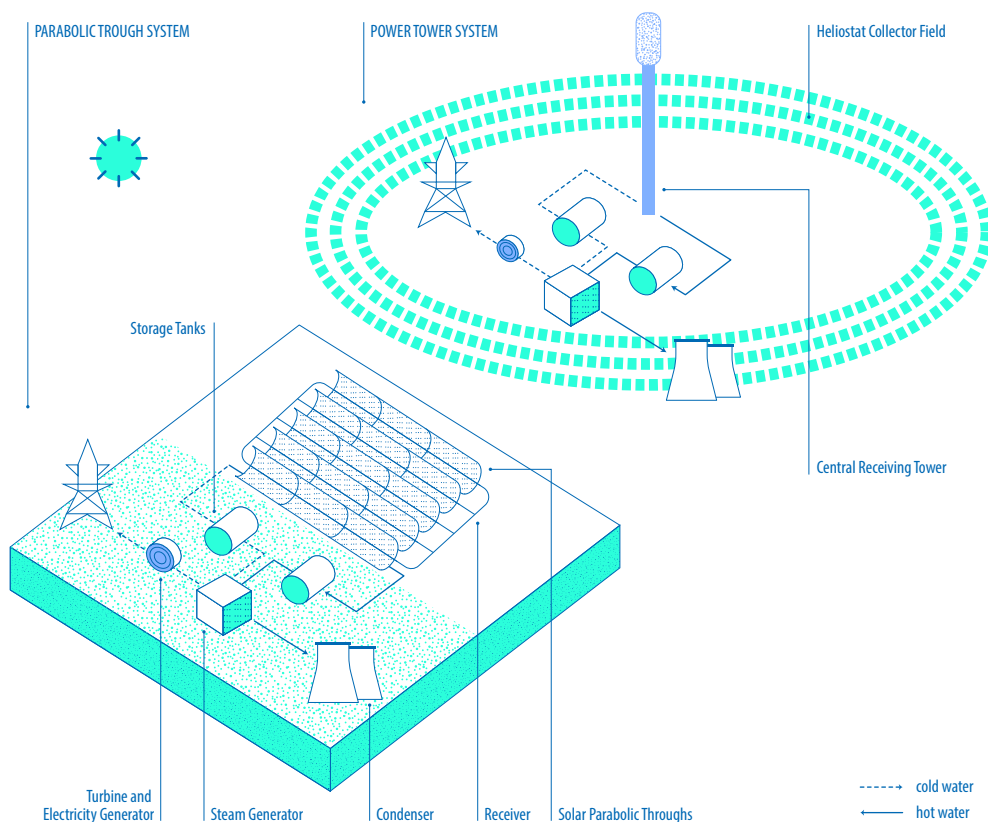
Inputs of materials and construction processes are also different for solar hot water and solar PV. As with other solar energy systems, solar hot water has potential life cycle impacts upstream and downstream from the installation, related to materials, construction and end-of-life disposal (See '*Renewable energy life cycle*'). Usually, these will not directly impact a property's Outstanding Universal Value, the attributes conveying it or other conservation values.

Concentrated solar power

Concentrated solar power (also called "concentrating solar power" or "CSP") involves the concentration of heat from sunlight. An array of reflectors is used to focus direct beam solar radiation on a receiver containing high-temperature heat transfer fluid, which in turn heats water to produce steam, turn a turbine and generate electricity. As well as a means of electrical generation, CSP may be used as a heat source for other industrial applications.

Compared to photovoltaics (PV), CSP technology has the significant advantage that it can be integrated with thermal energy storage to provide power that can then be transmitted to users when needed.

Unlike PV or solar heating, CSP cannot use solar radiation that has been diffused through clouds or dust. Most CSP plants have thus been built in desert areas with consistently clear skies. There are four main commercial designs in use or development: power towers and parabolic dishes (both concentrating onto a point), and parabolic trough and linear Fresnel collectors (both concentrating onto a line). Each design has technical strengths and drawbacks.



Main elements of a Concentrated Solar Power (CSP) station.

At present, by far the most widely used are:

- parabolic troughs, in which a linear assembly of parabolic mirrors tracks the sun and focuses onto a linear receiver tube, and
- power towers, in which an array of mirrors tracks the sun and focuses onto a central, fixed, tower-mounted receiver.

CSP is distinct from concentrator photovoltaics (CPV), which focuses sunlight onto specialized and highly efficient solar cells. CSP uses thermal energy while CPV, like conventional PV, uses the PV effect to generate electricity. Like CSP, CPV operates most efficiently in areas with clear skies that receive plentiful direct sunlight. CPV is less flexible and more expensive than conventional PV and lacks the dispatchable potential of CSP, so is not predicted to form a large component of future solar energy installations.

Potential impacts of CSP in World Heritage

Unlike solar PV, concentrated solar power (CSP) is generally developed at utility-scale, requiring a large area of land. Like utility-scale solar PV, CSP can have a substantial visual impact, particularly related to the tall central tower, but also the glint and glare from the mirrors and receivers. This can all be particularly significant, for example, when Outstanding Universal Value is related to the exceptional natural beauty and aesthetic importance of a cultural or natural World Heritage property or when the visual integrity of the landscape needs to be maintained.

The physical location of the CSP plant can have potential impacts on biodiversity through direct habitat loss, degradation and fragmentation; behavioural displacement that creates effective habitat loss; and the creation of barriers to movement and dispersal. It might also disrupt historical routes or disturb the traditional use or spiritual nature of heritage places. Siting needs to be carefully undertaken to take these issues into consideration. Refer to the section on potential CSP development impacts (See '*Solar energy projects and their assessment*') for details.

Some potential impacts are more likely to be significant for CSP than for solar PV installations. CSP involves more substantial constructed structures than solar PV, with potentially greater upstream and local impacts from sourcing, transporting and storing materials, and building or upgrading access roads. All construction work, including site levelling, excavation for foundations or cable trenches and surface hardening, etc., has the potential to damage or destroy archaeological remains. It is important to avoid sensitive cultural or archaeological sites and assess any potential archaeological interactions before siting CSP projects and, where necessary, carry out watching briefs during construction, as well as other preventive measures.

Compared to solar PV, the relatively large workforce required for construction and maintenance could also give rise to more significant indirect and induced impacts. The physical design of CSP installations, especially power tower CSP, may offer less scope than PV for impact reduction through micro-siting to avoid specific biodiversity features and minimize vegetation clearance and soil grading. For the same reason, there may be fewer opportunities, in general, for biodiversity enhancement at CSP plants than at PV installations, though such opportunities should be explored whenever feasible.

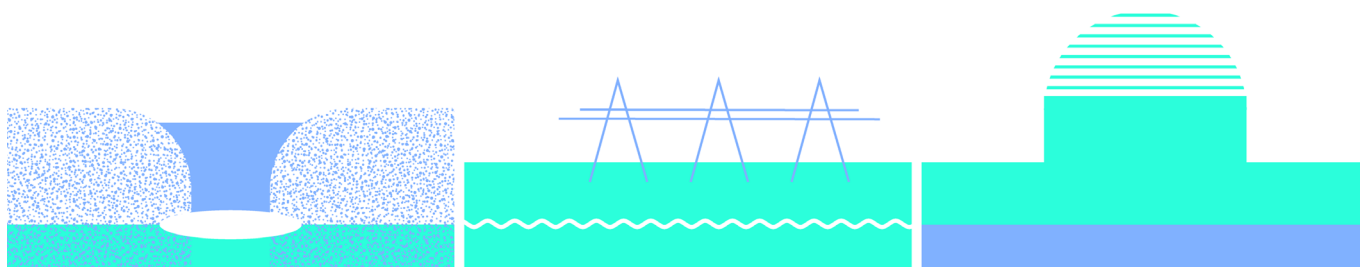
CSP plants are often located in arid, water-stressed areas, so water use is a significant environmental concern and may affect traditional water systems such as wells and irrigation. Wet-cooled CSP plants use very substantial quantities of water for cooling and discharging warm water into aquatic systems can also have negative ecological impacts. Dry-cooling systems (using ambient air or, in future, cool air pumped from underground) can mitigate these impacts, but may be less technically efficient.

As with solar PV panels, CSP plants may also use water to clean concentrator mirrors. Dry cleaning systems are an alternative, water-saving approach with reduced potential ecological impacts.

Fatalities of birds at CSP plants have been recorded, in small numbers, for individuals flying through the concentrated solar beams. Wildlife fatalities have also been recorded from poisoning or drowning in evaporation ponds, where wastewater used in cooling and/or cleaning is stored to concentrate chemicals before disposal. The risk of such fatalities can be reduced through appropriate design and, if necessary, deterrent features at evaporation ponds. Recycling wastewater can reduce the overall water-use footprint, but it must be properly treated and contamination reduced to safe levels before being discharged back into the environment.

Like solar PV, CSP has potential life cycle impacts upstream and downstream from the installation, related to materials, construction and end-of-life disposal (See also '*Renewable energy life cycle*'). Usually, these will not directly impact a property's Outstanding Universal Value, the attributes conveying it or other conservation values.

Transmission infrastructure essentials



Utility-scale wind and solar energy requires a suite of associated infrastructure to collect and distribute the electricity generated. Typically, the components of this infrastructure include cabling that goes from the wind turbines, solar PV panel arrays and thermoelectric generators to electrical substations, transformers to ensure the output of high-voltage electricity, and transmission lines to link to the grid and transport the electricity to further substations from which lower-voltage distribution lines supply it to users. All of these need to be constructed and serviced and road construction thus often forms part of the logistical development of utility-scale wind and solar energy projects.

Wind and solar PV farms may make use of pre-existing infrastructure, but often there is a need for at least a new substation, transformer and some length of new transmission line, as, in many cases, wind and solar projects are located in areas with no transmission assets and their large capacities require the construction of new assets.

At a general level, the renewable energy transition requires the complete electrification of energy end uses and the rapid scaling-up of renewable energy sources and, therefore, also a massive increase in transmission infrastructure. A typical electrical power transmission system consists of the following key components.

1. High-voltage transmission lines

- Conductors that carry electricity over long distances from the source (power stations including wind and solar power plants), with minimal loss, supported by transmission towers.
- Above-ground transmission utilizes tall lattice steel towers or monopoles to support high-voltage power lines. These towers are spaced over long distances to reduce interference and land impact. Above-ground lines are cost-effective but visually obtrusive and susceptible to weather-related damage.
- Below-ground transmission (underground cables) uses insulated high-voltage cables buried beneath the surface, reducing visual impact and exposure

to environmental conditions. However, underground transmission is more expensive due to the cost of insulation, cooling systems and maintenance access.

- Infrastructure considerations:
 - Subsurface tunnelling: For urban and environmentally sensitive areas, underground lines may be routed through tunnels.
 - Cooling systems: Since underground cables generate more heat, cooling methods such as liquid-cooled pipes or ventilation ducts are required.
 - Fault detection and maintenance: Advanced monitoring systems are necessary for identifying faults in underground cables, as repairs are more challenging than with overhead lines.

2. Substations

- Facilities that step up or step down voltage levels to ensure efficient power transmission and distribution.

3. Transformers

- Devices used to adjust voltage levels, either increasing them (step-up) for long-distance transmission or decreasing them (step-down) for distribution.

4. Converters

- Used in HVDC (High Voltage Direct Current) systems for long-distance transmission or interconnecting different power systems.

5. Circuit breakers and switchgear

- Protective devices that regulate power flow and isolate faults to prevent outages and equipment damage.

6. Control centres

- Facilities that monitor and manage the electrical grid, ensuring energy security, reliability and stability and responding to changes in demand.

Each component of transmission infrastructure systems can potentially create impacts that need to be considered in the context of a World Heritage property's Outstanding Universal Value and the attributes that convey it, as well as other heritage values. See also *'Transmission infrastructure projects and their assessment'*.

In most countries, the transmission infrastructure is part of national energy networks, therefore their extension, upgrading or modification typically implies strategic decision-making at national levels. As these plans could result in impacts for multiple heritage sites, including World Heritage properties, a strategic approach is needed to plan siting and design. See the information on *'Strategic Environmental Assessments'*.

When should a Strategic Environmental Assessment be considered?

A Strategic Environmental Assessment should typically be commissioned for a renewable energy policy, plan or programme so that:

- World Heritage considerations can be included at the earliest, strategic phase of energy planning so as to establish a framework that can inform all subsequent energy projects.
- a consistent approach to World Heritage protection can be taken nationally or regionally when planning for renewable energy, particularly when it is likely that there will be multiple authorizations for individual projects requested over time.
- instead of assessing only individual energy installations, the bigger picture is considered for all proposed energy projects, including related transmission infrastructure, access and transport routes, etc., located in or near a World Heritage property, its buffer zone, or wider setting.
- when development corridors or priority zones are designated, they are defined in accordance with World Heritage requirements and values, including specific Outstanding Universal Value and the attributes that convey it.
- land use or infrastructure development patterns, which may affect one or more World Heritage properties, are taken into consideration.
- long-term infrastructure development with (World-) heritage conservation goals can be coordinated at a regional or national scale.
- it can be checked whether the energy policy/plan/programme overlaps or interacts with other policies (e.g. multiple renewable energy strategies for solar/wind/etc., national grid upgrades, land use plans) that may influence heritage-sensitive areas.

See *'Strategic Environmental Assessments'*

Components of transmission infrastructure

Cables, transmission and distribution lines form the backbone of the power network, transporting electricity from generation sources through to end users. These lines are typically supported by pylons and towers that elevate and secure the cables across varying terrain and distances. The network is further supported by transformers and substations that regulate voltage, along with associated infrastructure such as access roads, maintenance tracks, control buildings and communication systems that enable safe, efficient and ongoing operation.

Cables

Cables are a key element in the electrical system of all electrical energy infrastructure. The installation and use of a multitude of cables is required: some are used to transmit the electricity produced to substations and the power grid (transmission cables), others to connect turbines (inter-array cables) or solar panels (solar arrays). They can be installed underground or overhead depending on the topography of the area and legal requirements (including heritage-related regulations).

Cables are also essential for connecting small-scale solar PV systems, located, for instance, on the roof of buildings, to inverters or batteries for local use, or to connect the solar PV installation to the grid. They need to be installed through or over buildings, or through or under a landscape.



Why is special attention needed for the design of cables?

Depending on the characteristics of a World Heritage property, both underground and overhead cables can pose challenges and have multiple potential negative impacts in relation to the Outstanding Universal Value and attributes of a World Heritage property. Among others, these could be:

- spatial disturbances, which could also lead to visual impacts,
- noise pollution,
- damage to archaeological remains (and their setting),
- habitat damage or loss,
- chemical pollution,
- the risk of entanglement for birds and other animals,
- sagging and significant risks to wildlife, endangered or protected species,
- reserve effects by excluding fishing,
- excess heat generation that affects habitat and species,

- electromagnetic field generation (EMFs) – this risk applies particularly to offshore installations, where EMFs have the potential to harm mussels, worms, electrosensitive cartilaginous fish such as sharks and rays, and bony fish such as eels.

It is very often necessary that the development of projects for cable infrastructure is assessed through either Strategic Impact Assessments at the policy phase, or through Environmental Impact Assessments (EIAs) or Heritage Impact Assessments (HIAs) at a project level.

See also the section on 'Assessing Impacts'

Transmission and distribution lines

The regional or national electrical infrastructure (or electrical grid) consists of transmission lines and distribution lines. Transmission lines carry high-voltage electricity from the production source to substations where the voltage is lowered. From there, distribution lines connect to neighbourhoods or sites with other end uses. It involves a series of electricity pylons or transmission towers connected by multiple cables that can extend to long distances. When extending beyond national boundaries, these are referred to as a supergrid. Typically, utility-scale solar PV and wind energy installations do not involve the construction of new transmission lines. However, upgrading existing transmission and distribution lines or developing new transmission or distribution infrastructure may be part of the project's associated infrastructure in some cases, including for micro-grids (small, self contained power networks) or for cabling between turbines or panels and a substation.

Transmission towers and cables are highly visible structures that could significantly impact Outstanding Universal Value related to a property's exceptional natural beauty and aesthetic importance. Even when located in the wider setting, their presence can have a negative impact on the way in which the setting of a World Heritage property supports its Outstanding Universal Value.

Distribution lines can also have consequences on a small scale, for instance, where they connect to historic buildings. All distribution installations need to be designed with the appropriate considerations.

Distribution lines within the territory of a wind or solar PV farm can often be buried, which avoids potential electrocution hazards. This approach can also be applied as good practice, with appropriate preventive archaeological measures in place.

Poorly designed distribution lines can pose a high risk of fatal electrocution to certain species, notably birds with large wingspans that may perch on power poles. These risks can be easily minimized at minimal cost by using wild-life-friendly designs for poles, cables and insulators. Some bird species are at risk of fatalities from collision with transmission lines and cables, especially the thin earth wires that run above transmission cables and are relatively hard to see. The risk is greatest for large species with relatively low manoeuvrability. Lines placed near areas where birds congregate, such as wetland sites, also pose a high risk, as birds may not be able to gain enough height to clear the cables after take off. Good practice mitigation involves routing lines away from high-risk sites and fitting appropriate bird diverters on earth lines (balls, spirals or flappers to make the cable more conspicuous). Where night-flying species (e.g. flamingos) are at risk, illuminated diverters are appropriate. If high-risk sites cannot be avoided, burying cables may be the only viable option for mitigation.

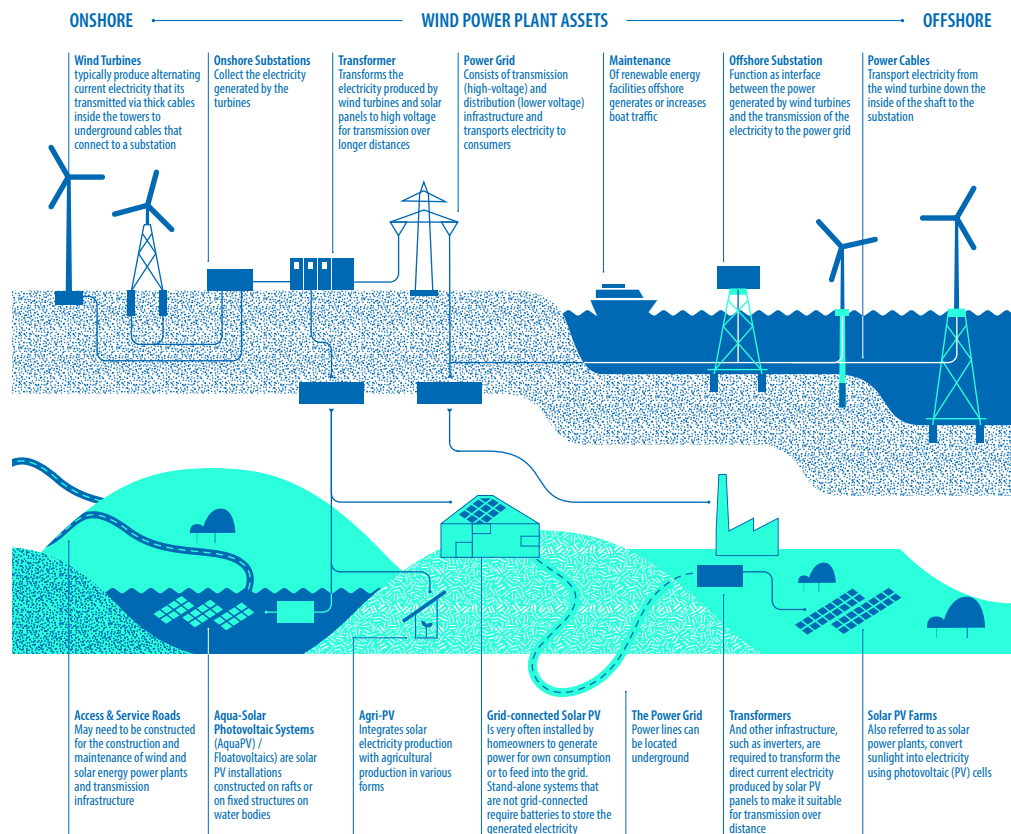
Some open-country bird species show displacement behaviour and are reluctant to forage or nest near turbine towers. This leads to the effective loss of their habitat. Such risks need to be assessed through thorough ecological surveys prior to construction and mitigated as far as possible through the re-routing of transmission lines.

Options for transmission-line location and routing need to be carefully considered with this in mind. Burying particular stretches of transmission line, although an expensive option and with other potential impacts on archaeological features, is a possible mitigation measure for particularly significant viewsheds.

Undersea cables can potentially impact marine species through electromagnetic fields (EMFs) and, during installation and decommissioning, seabed disturbance and sediment suspension. The significance of impacts from EMF disturbance is poorly understood and is currently the topic of continuing research. However, undersea cables should be sited to avoid sensitive seabed habitats and traditional fishing grounds.

Access roads along powerline rights of way can potentially fragment natural habitats and landscapes, create risks to wildlife from vehicular disturbance and collisions, and facilitate human access to previously undisturbed areas. They can alter land use patterns in cultural landscapes and may also intrude on sacred or spiritual land. These risks can be minimized through:

- careful design, tested through appropriate impact assessments,
- controlled and careful operation,
- the control of access roads and maintenance operations,
- collaboration with Indigenous Peoples and local communities, and
- monitoring and maintenance protocols.



Wind and solar energy, and transmission infrastructure in a schematic landscape/seascape.



Designing power grids

As countries expand renewable energy infrastructure, the design and placement of power grids, including pylons, towers, substations and transmission lines, must be approached with special care when near or within the wider setting of a World Heritage property. These installations, though essential for energy distribution, can have unintended visual, physical or cultural impacts if not carefully planned.

To minimize negative effects, it is vital that the siting and design of power grid infrastructure be carried out in close coordination with heritage protection authorities. This ensures that decisions reflect a deep understanding of the site's Outstanding Universal Value – the very qualities that earned it World Heritage status.

Planning with sensitivity and understanding

- Vulnerability assessments and sensitivity maps (See 'Vulnerability assessment of World Heritage properties' and 'Vulnerability mapping in urban World Heritage environments as a tool to facilitate renewable energy installations') can help to guide the placement of infrastructure, especially when determining the routing and spacing of pylons or towers.

- These tools identify areas where the property is visually or ecologically sensitive, enabling informed design choices.

Design solutions that respect the heritage place

- **Topography:** Planners can use natural variations in terrain – such as hills, trees, or valleys – to screen pylons or ancillary features from key views or cultural landscapes.
- **Contextual fencing and barriers:** Where fencing is required for safety or agricultural protection, it should blend with local landscape traditions.
 - For instance, in rural areas where dry stone walls are a traditional feature, it is better to use local stone and building styles than industrial fencing such as steel palisades.
 - This helps to maintain the integrity of the visual and cultural landscape, supporting both heritage protection and community identity.

Power grid development near World Heritage properties should not be treated as a standard infrastructure task. Instead, it requires site-specific solutions, early dialogue with heritage authorities and a landscape-sensitive approach that protects the value of World Heritage for future generations.

It is very often necessary that project development for power grids is assessed through either Strategic Impact Assessments at the policy phase, or through Environmental Impact Assessments (EIAs) or Heritage Impact Assessments (HIAs) at a project level.

See also the section on 'Assessing Impacts'

Transformers and substations

A transformer is a device that transforms the energy produced by energy infrastructure such as solar or wind installations into higher voltage electricity and feeds it into the power grid via cables, or to lower voltage to feed it into lower voltage distribution networks. It is connected by cables to one or more substations. The size and type of a transformer depends on the type of receiving substation and the generation capacity of the renewable energy project.

There are different types of transformers, including oil filled, dry type, shell type, core type, single-phase and three-phase transformers.

Substations are essential annexes for utility-scale renewable energy installations. They function as the interface between the power generated by the wind turbines or solar panels and the transmission of the energy into the electricity grid. Substation compounds usually include:

1. Transformers or converters, circuit breakers, capacitors, relay and control systems, lightning arresters, busbars;
2. control, protection and metering systems that enable the correct operation of the wind farm according to local regulations and grid requirements;
3. communication systems made of optical fibre or wired cables – these guarantee the correct communication with the nearby substations and with the grid control centre;
4. protection systems against fire and intruders – these include detectors, sirens and fire extinguishing tools, as well as fences and lighting.

In the case of offshore wind or solar energy projects, the transformer (also called the converter station) can consist of medium to large offshore or onshore infrastructure, usually connected to one or more substations.

Operating transformers emit a low-frequency hum, which can disturb the quiet. Substations and transformers can potentially be attractive to wildlife, because they produce a warm microclimate and are brightly lit up at night. This

can create potential electrocution or collision hazards. Additionally, transformers pose a potential risk of oil leaks and fires, which could threaten surrounding flora, fauna or heritage sites. The use of dry-type transformers can remove the risk of contamination from leaks. Baseline ecological surveys can identify potentially at risk species, which should inform design and operations to minimize impacts (e.g. installing appropriate fencing for facilities, screening off potential perch sites and replacing continuous lighting with flashing strobes).

The construction of substations and transformers in historic areas, cultural landscapes and other sensitive areas should be carefully considered, not only from the perspective of their visual impact, but also from a safety perspective. They can, if not well considered, result in the jarring presence of a discordant technological intervention in a historical landscape.



Specificities concerning offshore substations

Offshore substations are placed on the sea in the proximity of their wind farms or parks. These are generally large structures weighing between 400 and 22,000 tons. They are built on fixed foundations – either steel monopile foundations, larger jacket foundations or concrete gravity based structures.

These substations collect and transform the electricity generated by the wind turbines, stepping the voltage up for efficient transmission to shore. Their operation requires associated infrastructure such as undersea cables, scour protection systems, boat landing platforms and helicopter decks, all of which can increase the footprint of the installation. Depending on its location and layout, they may be visible from coastal World Heritage properties or influence marine ecosystems relevant to the property's Outstanding Universal Value.

The construction and maintenance of offshore substations may also involve activities with significant impacts such as pile driving, dredging, cable trenching and vessel traffic, which could disrupt marine habitats and migration routes. In cases where World Heritage properties include or are adjacent to marine areas, or where their settings include open seascapes, the siting, scale and cumulative effects of offshore substations should be subject to Strategic Environmental Assessments.

See also the information on 'Strategic Environmental Assessments'.

Light and noise from substations near heritage places may also have negative impacts on the sense of the place and for associated communities, so the specific context needs to be assessed in advance so appropriate siting can be identified.

As substations require significant periodic maintenance, access roads will necessarily be one of the points to consider about their location.



Reducing the risk of fire and explosions at transformers and substations

Electrical transformers and substations play a critical role in energy transmission, but they also carry inherent risks. Fires or explosions can occur due to equipment failure, overheating and electrical faults such as short circuits and sparks. These incidents can cause not only serious safety hazards for personnel but also major power outages and environmental damage.

A particular concern is oil-filled transformers, which use flammable insulating oil. If this oil is exposed to excessive heat or sparks, it can ignite, escalating a small fault into a large-scale fire.

How to reduce the risk

The prevention of such incidents depends on routine maintenance and early fault detection.

Key actions include:

- carrying out regular inspections to detect physical damage or wear,
- using thermal imaging to identify overheating or 'hot spots',
- conducting oil quality tests to check for the contamination or breakdown of insulation properties,
- conducting electrical tests to detect insulation faults or abnormal current levels,
- cleaning and tightening connections, especially in high-voltage areas,
- ensuring proper ventilation to reduce heat build-up,
- upgrading or replacing outdated components.

To limit damage if a failure does occur, facilities should also install:

- fire suppression systems (e.g. gas, water mist or foam systems),
- protective relays, to isolate faults quickly and prevent cascading failures.

Consistent maintenance and preventative measures are essential to keep transformers and substations safe and reliable. By acting early, operators can significantly reduce the risk of incidents and ensure continued service and safety.

Access roads and tracks

The construction, maintenance and decommissioning of wind and solar farms and high-voltage transmission infrastructure and the transportation involved therein require access tracks and, in the case of offshore development, harbours. Wide and sturdy roads or tracks are needed to provide access to substations and to the bases of wind turbines. Roads are also required to access the routes of transmission infrastructure, although helicopters can be utilized to construct high-voltage lines in inaccessible environments. Roads and tracks are usually created either by improving the capacity and width of existing road infrastructure or by building new access roads. Likewise, harbour facilities with their own access roads may need to be upgraded or created to accommodate the construction and maintenance of offshore renewable energy facilities.

The technical requirements may vary for this infrastructure during the different life cycles of offshore wind renewable energy facilities. For example, the transportation of wind turbine components such as blades requires wide, straight roads without bulges or dips in the roadway, and there are specifications on the types of materials needed for construction. Solar development typically requires smaller modules, so smaller and less equally graded roads can suffice. Offshore renewable energy projects require the establishment of marine routes for the vessels involved in the operation, including the maintenance of turbines and ancillary facilities or the maintenance of floating photovoltaic (PV) infrastructure.



Designing access roads and tracks

The construction, operation, maintenance and eventual decommissioning of renewable energy infrastructure can significantly increase traffic and physical alterations to landscapes. While access roads and tracks may seem like minor elements compared to wind turbines or solar farms, they can have far-reaching consequences – especially when projects are located near or within the wider setting of a World Heritage property. Even when the project site itself is outside the inscribed property or buffer zone, construction traffic and associated infrastructure can directly or indirectly impact the attributes that convey a site's Outstanding Universal Value (OUV). These impacts may affect not only cultural or scenic elements, but also local communities, ecosystems and wildlife.

Key planning considerations

- Traffic impacts (dust, noise, vibration and emissions) can disturb heritage features, habitats and communities, especially during the construction phase.
- New road development must take into account:
 - the location of sensitive cultural or natural attributes,
 - the visual and physical character of the surrounding landscape,
 - existing heritage values, even outside official boundaries.

Designing with sensitivity

- Road alignments must avoid crossing or fragmenting areas with OUV or related heritage values.
- In sloped or topographically complex terrain, road building may require cutting, filling or slope stabilization. These modifications can:
 - visually scar cultural landscapes,
 - alter ecological systems,
 - disrupt traditional land uses or practices.

In such cases, alternative alignments should be explored to better integrate roads into the landscape and avoid or reduce harm to heritage values.

Marine contexts also matter

For offshore renewable energy projects, access is not provided via roads but shipping routes and support vessels. Still, similar principles apply.

- Route planning must consider the migratory paths of seabirds and the travel patterns of marine mammals.
- Sites important for breeding, feeding or resting – whether inside the property, its buffer zone or its wider setting – must be protected from noise, collisions and traffic-related disruption.

Access roads and service routes are not just technical necessities, they are part of the broader project footprint. Their design must respect and protect the cultural, natural and intangible attributes that contribute to the OUV of nearby World Heritage properties.

Renewable energy life cycle

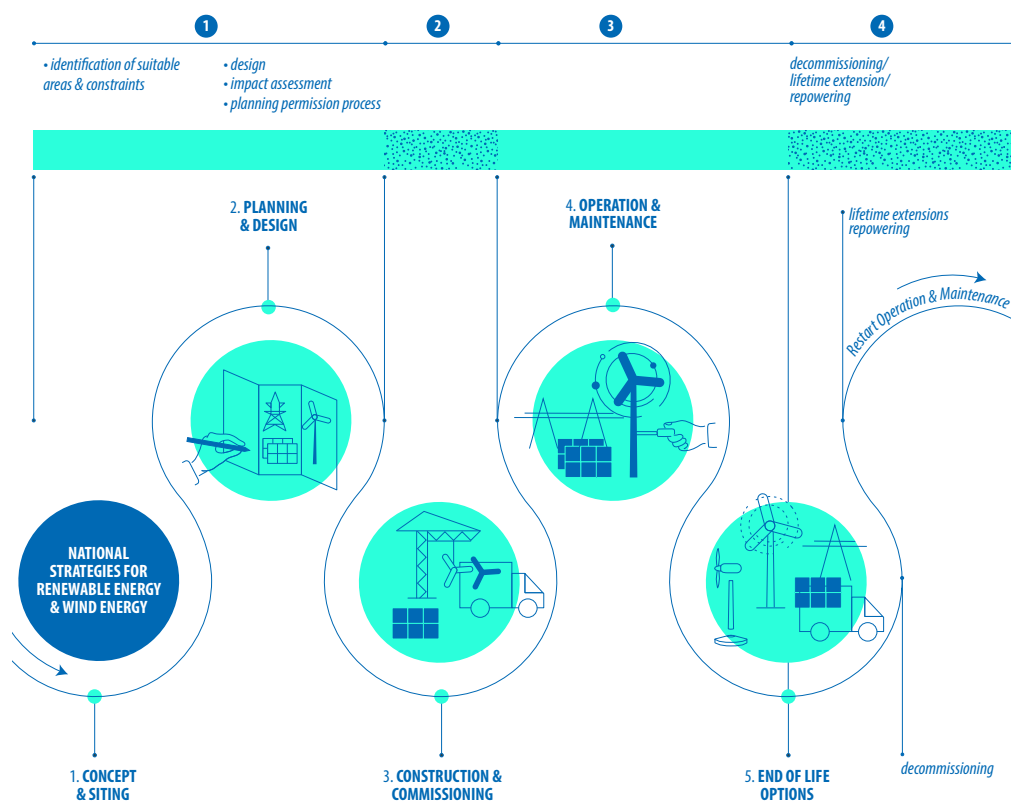
The potential impacts of renewable energy projects on World Heritage properties also need to be assessed regarding the different phases of a project life cycle. Impacts may differ from phase to phase, some occurring throughout the life cycle of a project and others only for a short period of time or at seasonal intervals. (See also information on assessing the impact of a proposed project over its entire lifecycle in 'Environmental and Social Impact Assessments and Heritage Impact Assessment'.)

From planning to commissioning

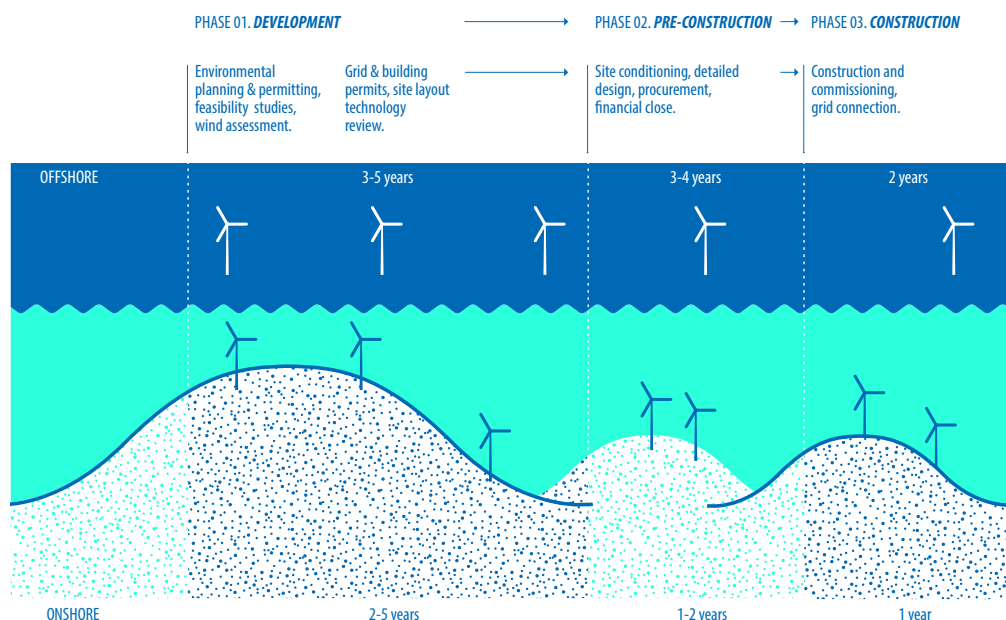
This project phase includes both strategic and detailed planning for the development of a renewable energy installation (usually the construction of several wind turbines or a solar PV farm) and the commissioning of the project (which is a set of activities performed before an operation permit is provided to confirm that the wind turbines or solar PV array have been correctly installed and that they are ready for energy production). It is characterized by a significant lapse of time and there can be several years between the planning and operational phases.

This phase includes several activities:

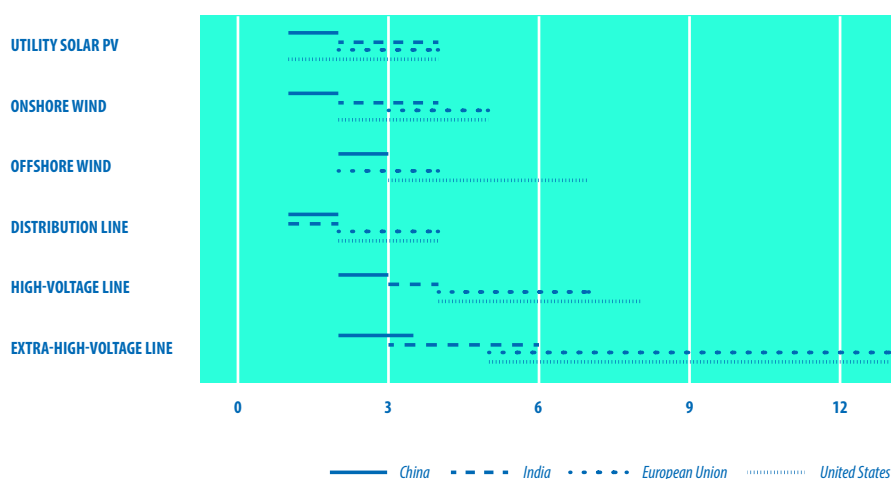
- compliance with spatial planning regulations,
- assessment of resources and wind or solar energy potential,
- identification of land available (purchasing or leasing),
- identification of potentially suitable areas for the project,
- consultation with rights holders and stakeholders,
- engagement of other World Heritage actors,
- site analysis through calculations and digital modelling, allowing for the identification of the most appropriate location and type of installation,
- early assessment of the technical feasibility of the project,
- identification of regulatory constraints,
- design of the installation (including the size and model of wind turbines, the colour and siting of solar PV arrays, technological characteristics, electrical design and infrastructure plan),
- impact assessment and other technical studies (for example, risk screening, biodiversity assessment, biodiversity sensitivity mapping, setting studies),
- preparation of the planning permission process,
- securing of financial mechanisms,
- construction of the renewable energy installation and ancillary facilities,
- commissioning (which covers all activities after the installation of the wind turbines is completed).



Lifecycle of larger scale wind and solar energy projects. (Note that the image does not include the 'sourcing' and 'recovery' phase of these projects.)



Average timespan of steps from 'planning' to 'commissioning' of wind energy projects in Europe (source: [Wind Europe](#))



Typical deployment time for electricity grids, solar PV and wind development (Adapted from: *Electricity Grids and Secure Energy Transitions*, IEA, 2023).

The average approval and construction times for renewable electric power developments (electricity grids, solar PV, onshore and offshore wind farms) vary widely. In advanced economies, it is not uncommon for a single overhead power line to take five to 13 years to be granted approval and built, depending on the length of the line and other factors. Lower-voltage projects are faster and take four to eight years on average. Distribution network projects are usually completed within four years on average.

The International Energy Association (IEA) updates its *World Energy Outlook* annually. This report provides, amongst others, insight into deployment (planning, approval and construction) times of different energy technologies.



Why are impact assessments essential in an early project phase?

When planning wind or solar energy projects near a World Heritage property, it is critical to understand how the development might affect the property's Outstanding Universal Value (OUV) – not just the site itself, but also its attributes and wider setting.

To ensure responsible development, the potential impacts on the attributes that convey OUV should be assessed as early as possible in the project life cycle, ideally during the screening and scoping phases of the impact assessment. (See also the section on 'Assessing Impacts'.)

Conducting this assessment early has several important advantages, as it:

- identifies risks before major investments are made, allowing time to adjust project plans,
- supports informed siting and design, potentially avoiding sensitive areas from the outset,
- strengthens collaboration with heritage authorities, communities and other stakeholders,
- reduces costly redesigns, delays or rejections later in the process.

Early screening can change the direction of projects

Sometimes, initial findings during screening or scoping clearly reveal that:

- a project would have unacceptable adverse effects on a World Heritage property's key attributes,
- the proposed location or design is incompatible with Outstanding Universal Value.

In such cases, decision-makers and project developers may need to:

- explore alternative sites or configurations,
- consider halting the project entirely.

While this might seem like a setback, making such decisions early in the process can actually save time, resources and reputational risk in the long run. It also helps to maintain the integrity of one of the world's most valued heritage assets.

Early impact assessment is not just good practice – it's a smart strategy for ensuring that both renewable energy goals and heritage protection can be achieved in parallel.



A good example of a national-level guidance document is *Siting and Designing Wind Farms in the Landscape* (2017), prepared by Scottish Natural Heritage. The document advises on the siting and design of wind farms in Scottish landscapes. It describes an iterative design process involving the assessment of landscapes and the visual effects of wind farms. See also the examples included in *World Heritage and wind energy planning: Protecting visual integrity in the context of the energy transition* (2021), and the EU *Guidance document on wind energy developments and EU nature legislation*, (2020), which provides information on wind energy development and certain aspects of EU nature legislation.

Operation and maintenance

The operation and maintenance phases of wind and solar farms generally span 20 to 25 years with a possible extension of the lifespan of up to ten years. Solar PV panels and solar hot water collectors have, at present, a life expectancy of 25 to 30 years. For utility-scale projects, operation and maintenance phases start after a testing period and upon approval of the purchase agreement for the produced electricity by the relevant national, regional or local authorities or energy companies. This phase includes the routine servicing and repairs that are required to achieve continuous operation and maximize the installation's designed lifetime and to ensure compliance with financial, safety, security and leasing agreements.



Potential impacts in the operation and maintenance phase

When wind and solar energy facilities and transmission infrastructure are built and in operation, their impact might be especially averse to World Heritage properties with:

- particular landmarks in the landscape,
- important visual relationships between different attributes (lines of sight, panoramas, vistas, skylines),
- a notable landscape or townscape morphology,
- spiritual or other traditional associations,
- picturesque elements and points for the appreciation of the landscape's beauty,
- natural features of elements and areas, including landscape features and geological and physiographical formations (mountains, peaks, glaciers, lakes, rivers),
- natural phenomena or areas of exceptional natural beauty and aesthetic importance,
- migratory processes,
- ecologically sensitive areas and key biodiversity areas (KBAs);
- agricultural areas or areas with important seasonal activities.

Impacts can vary greatly depending on the different types of attributes. It is important to remember that impacts must be assessed in relation to attributes that are already at a very early stage for each project. See also the section on 'Assessing Impacts'.

A comprehensive list of potential impacts on nature and biodiversity can be found in the IUCN publication *Mitigating biodiversity impacts associated with solar and wind energy development. Guidelines for project developers* (2021).

End-of-life options

Lifetime extension

Through the partial replacement of components (e.g. the blades or gearboxes of wind turbines), the lifetime of wind energy installations can be extended. For wind turbines, this can extend the life of an individual turbine by ten years to a total of up to 30 to 35 years. To prolong an already approved and licensed lifetime, a remaining useful life (RUL) assessment (i.e., a fatigue analysis) needs to be undertaken in combination with a site inspection and review of the maintenance framework. As a result, owners of wind turbines may be required to undertake certain repair works and reinforce or renovate certain areas.

Solar systems are more flexible and the replacement of solar PV panels or hot water collectors would effectively herald a new life cycle (through repowering), which may require new licensing or the extension of existing licence agreements in the case of large-scale installations.

Repowering

Repowering means replacing existing infrastructure with newer generation technology in the same designated area.

For wind energy, this generally results in replacing older wind turbines with taller, more powerful ones, the end result being fewer, larger turbines in the same area. For solar energy, advancements in solar PV technology could lead to higher energy production or to changing appearances, including through options for camouflaging solar PV panels by changing their colour or texture. Revamping and repowering refer to the replacement of the old PV system components of a power plant with newer ones to enhance the overall performance of the plant. Revamping involves replacing components without substantially altering the plant's nominal power, whereas repowering involves increasing the plant's capacity. As solar PV repowering activities continue to grow, the solar sector has developed best practices to guide these initiatives.

Replacing PV modules prematurely presents a complex sustainability challenge. On one hand, reducing the lifespan of durable products contradicts the circular economy goals of minimizing waste and conserving resources. On the other, rapid advancements in solar PV technology have significantly improved efficiency and performance, making upgrades attractive. To balance these factors, the sector engages in revamping and repowering efforts, upgrading outdated components to enhance overall system output. While such upgrades may generate PV waste sooner than expected, they also enable higher energy production, leading to a greater reduction in greenhouse gas (GHG) emissions.

The decision whether to repower or simply decommission a renewable energy plant mainly depends on:

- the performance of the renewable energy plant and the cost of operation and maintenance;
- the remaining lifespan of support frameworks/mounting structures (generally 20 years);
- the land-use permits or lease extensions, policy support and renewable targets;
- the evolution of wholesale electricity market prices;
- Technology evolution and space optimization with more efficient panels generating more power in the same area, allowing for capacity expansion without requiring additional land.

The regulatory framework and environmental restrictions

Policies focusing on repowering may vary considerably from country to country. Whereas repowering may require a whole new permitting process including impact assessments (usually as part of an Environmental and Social Impact Assessment (ESIA)) and the examination or re-examination of the suitability of an area in one country, it may only take a 'fast-tracked' permission request in another. In addition, not all previous wind or solar PV farm areas necessarily remain eligible for repowering, in which case an alternative end-of-life scenario will need to be considered (i.e., lifetime extension or decommissioning).



Reversibility, lifetime extension and repowering

Wind and solar PV farms are often viewed as temporary structures with largely reversible impacts. In theory, at the end of their operational lifespan – typically between 20 and 35 years – these facilities can be dismantled and the site restored to its previous condition. This process is usually guided by a decommissioning plan, which should be defined in advance and embedded in permitting procedures for construction and dismantling.

However, in practice, true reversibility is rarely simple and several factors influence whether a site can genuinely be returned to its pre-project state.

These include:

- the design characteristics of the energy project such as location, installation density, land grading and the materials used,
- the presence of foundations, access roads and ancillary infrastructure (especially relevant for wind turbines),
- the nature and sensitivity of the World Heritage property and the attributes that express its Outstanding Universal Value (OUV) such as archaeological layers, geological formations and delicate hydrological systems.

See also the section on 'Assessing Impacts'.

What mostly happens after 30 years?

In many cases, rather than dismantling infrastructure, project developers seek to extend the facility's lifespan or undertake repowering – the replacement of ageing equipment with newer, more efficient systems. While technically beneficial, repowering is not a neutral activity from a heritage perspective. It usually triggers a new (though sometimes simplified) permitting process and may require an updated Environmental and Social Impact Assessment (ESIA) or Heritage Impact Assessment (HIA).

Regardless of whether a project is new, extended or repowered, the same rigorous level of impact assessment should be applied. This ensures consistency in safeguarding the OUV of the World Heritage property across the full project life cycle of development, operation and renewal.

Dismantling is not a sufficient mitigation strategy

Importantly, if a wind or solar project – along with its transmission infrastructure – has adverse impacts on the attributes conveying OUV, the possibility of dismantling it in the future does not qualify as mitigation. The argument that 'the installation is only temporary' is not an acceptable justification for approving a project that may cause irreversible harm. Instead:

- potential adverse impacts must be addressed upfront, during the initial assessment and design stages;
- restoration options should be explored as part of the impact assessment process;
- no assumptions should be made about reversibility unless there is clear evidence and planning in place.

Reversibility and repowering should never be taken for granted in the context of World Heritage. Each proposal must be evaluated with a clear understanding of its full life cycle and potential effects on the values that underpin the site's international protection. Only by applying consistent, evidence-based assessments can the needs of clean energy development be balanced with the enduring responsibility of protecting World Heritage for future generations.



Repowering and World Heritage

In 2023, the European Union revised its [Renewable Energy Directive](#) (2023). It now says that EU countries must make it easier and quicker to approve upgrades – called repowering – to existing renewable energy sites, like wind farms. Even though these upgrades still need official permission, the process should be faster, since the land has already been approved for wind energy use.

WindEurope, a leading wind energy organization, suggests that when assessing the environmental impact of the new wind turbines, the comparison should be made with the existing site, not with a site that has never had turbines before (a "greenfield" site).

However, from a World Heritage point of view, this faster process doesn't mean skipping important steps. If the repowering project is near a World Heritage property, it should still go through a proper impact assessment. This should look at how the upgraded site could affect the property's Outstanding Universal Value, starting with the official Statement of that Value. The assessment should also consider whether it might be better to remove the site entirely and restore the land instead of repowering.

Decommissioning: dismantling, removal, re-use, rehabilitation/restoration, recycling and recovery

Decommissioning is the process of removing wind energy infrastructure from an area. This phase consists of the dismantling and removal of the renewable energy systems and all other connecting infrastructure, including the treatment and recycling of waste and materials. Following this process, the area ideally needs to be fully cleaned and the land restored to its original condition. The extent of removal and rehabilitation during this phase depends to a great extent on the respective national policies and specific national guidelines, if available, for the dismantling and demolition of wind turbines and other project-specific infrastructure. If not specified otherwise, the decommissioned site should be restored to greenfield.

A detailed decommissioning plan is typically a mandatory part of large-scale renewable energy projects such as wind or solar PV farms. It is examined and approved as part of the application process. This plan should later guide the removal of the installation and specify responsibilities and who would bear the costs. The plan usually reflects contracts regulating land use and grid connection points and refers to the conditions imposed by local authorities through the building or demolition permits, as well as to relevant national, regional or local legislation.

Accordingly, renewable energy licences, contracts and plans need to include provisions for the removal of infrastructure and the restoration of the land to its original state after the permanent decommissioning of the wind or solar farm and, if relevant, the ancillary facilities as well.

A growing yet relatively small share of solar PV module capacity is reaching the end of its economic lifespan. While some decommissioned panels are damaged or faulty and must be discarded, a substantial number remain in good working condition and could still contribute to the global clean energy transition. As a result, the solar industry is increasingly focused on developing efficient methods to sort, repair and repurpose these components. This issue is becoming even more relevant as repowering and revamping activities rise, with many PV systems being replaced due to economic factors rather than technical failures. Reusing functional PV modules or inverters helps to reduce waste and pollution while also creating economic opportunities. Additionally, it supports compliance with regulatory requirements (notably the European Union's Waste Framework Directive) and strengthens the sector's commitment to sustainability and circular economy principles. While, in 2025, no established standards, norms or technical specifications yet exist for the reuse of PV modules, they are being developed.



Case Study

[Repowering the Floriana Island \(Galápagos Islands, Ecuador\) solar PV power plant](#)



Guidance on decommissioning renewable energy projects

Responsible companies in the renewable energy sector are taking steps to reduce the environmental impact of wind and solar installations after they reach the end of their use.

- WindEurope published [decommissioning guidance](#) for onshore wind turbines in 2020, to be used where national rules are lacking.
- SolarPower Europe released [best practice guidelines](#) for managing the end-of-life phase of ground-mounted solar PV systems in 2024.

In other regions:

- in the United States of America, the National Renewable Energy Laboratory (NREL) has reviewed [solar energy decommissioning policies](#) at federal and state levels, including land restoration and solar PV removal;
- the Government of the United Kingdom of Great Britain and Northern Ireland provides legal and [technical guidance](#) for dismantling offshore wind farms;

- Australia's Clean Energy Council offers [procedures for decommissioning offshore wind turbines and recycling solar PV systems](#);
- in Canada, the Canadian Renewable Energy Association (CanREA) shares [best practices](#) for decommissioning both wind and solar projects.

However, Africa, Asia and South America currently have few formal decommissioning guidelines.

Efforts are underway in several countries to develop supranational standards.



Removing wind and solar facilities

What to consider from a World Heritage perspective

Wind and solar farms usually operate effectively for 25 to 30 years. However, planning for what happens after that – including how the land will be restored – should begin before construction even starts.

From a World Heritage perspective, this means:

- the project's impact assessment should consider how all stages (construction, operation and decommissioning) may affect the property's Outstanding Universal Value and key attributes;
- mitigation and restoration plans must be developed early and included in:
 - licensing documents,
 - the environmental and social management plan,
 - other project management and operational documents.

These documents should:

- be shared with all relevant parties (e.g. site managers, local authorities, contractors),
- be followed throughout the life of the project, especially during decommissioning.

See also the section on 'Assessing Impacts'.

At the end of the project's life, the operator must ensure that removing the facility does not harm the attributes that make the nearby World Heritage property significant. Restoration work must be done carefully and responsibly to meet these standards.

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