Engineering our way to a safer and more sustainable end of life for critical renewable energy infrastructure

© Adobe Stock

Engineering X

Royal Academy of Engineering

LR Foundation

Introduction

This spotlight looks at the engineering issues linked to the end of life of renewable energy infrastructure and the roles and responsibilities of engineering professionals, governments and industry in developing the engineering capacity to tackle these challenges. This spotlight primarily focuses on the end of life of solar photovoltaic (PV) technology and wind turbines as an example of the associated challenges and hurdles. In particular, it highlights the need to plan now for the end of life of renewable energy technologies and infrastructure components that are being designed today.

In the past decade, the renewable energy sector has experienced an unprecedented surge in growth and scale worldwide. S&P Global Commodity Insights found that solar panel module installations surged by 17% between the first and second quarters of 2023. Projections indicate that installations rose 27% in 2024 and will slow to an 8% increase in 2025.[1]

Global cumulative wind power capacity surpassed the 1 TW mark in 2023[2], and 106 GW of onshore wind capacity was added to the grid in the year, a growth of 54% year on year.[3] A total of 10.8 GW of new offshore wind capacity was also installed in 2023, raising the global total to 75.2 GW, a 24% increase over 2022.[4] The wind industry must roughly triple its annual growth from a level of 117 GW (onshore and offshore) in 2023 to at least 320 GW by 2030 to meet the COP28 targets and steer the world back onto the 1.5°C pathway.[5]

Continued growth in renewable energy infrastructure is clearly much needed. However, as the number of structures increases, this also raises challenges. One of these is considering how to safely and sustainably manage this growing asset base of renewable infrastructure when it reaches the end of its design life.[6]

1 PV Module Supply Chain Tracker. Q4 2024 (9 Dec 2024). S&P Global Commodity Insights.
2 PV Module Supply Chain Tracker. (n.d.). [Data set]. S&P Global Commodity Insights.
3 Global Wind Report 2023, Global Wind Energy Council, 2023, at https://www.gwec.net/reports / globalwindreport/2023 (retreived 13 May 2025).
4 ibid.
5 ibid.
6 End of design life here is used to emphasise the need for circularity and the idea that there are still many options for extension and reuse even after a product has reached the end of the period of time it was originally designed for.

Figure 1: Global solar demand

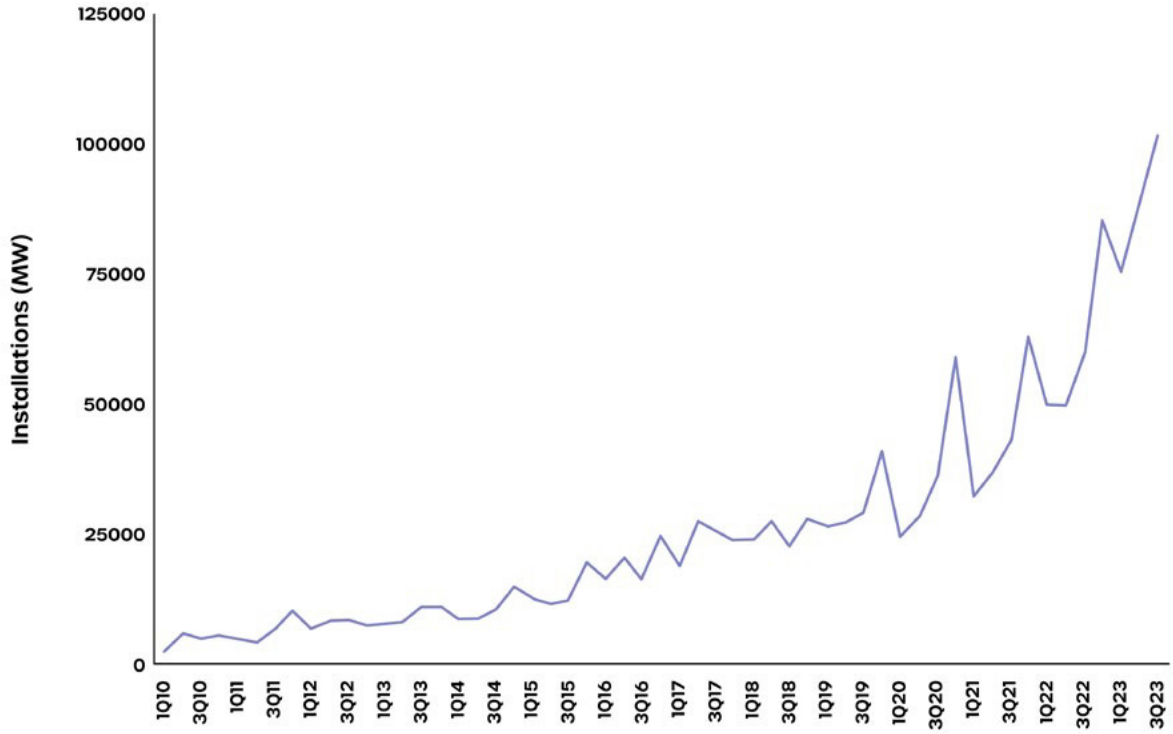
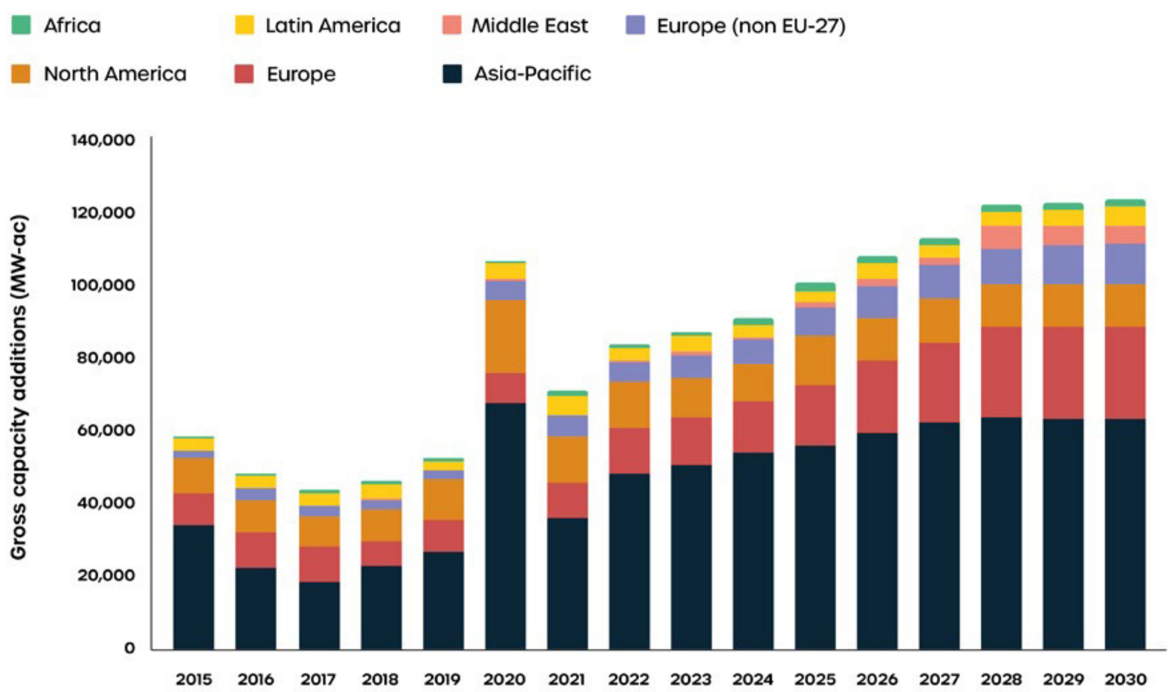


Figure 2: Onshore wind market outlook



The stakeholder groups outlined in the Engineering Capacity Index (ECI) – government, engineering industry and professional engineers – have a vital part to play in cultivating the required capacity to ensure safe and effective end-of-life management.

What are the key challenges associated with the end of life of renewable energy infrastructure?

The rapid expansion of renewable energy requires careful consideration of the engineering capacities needed to effectively manage the end-of-life process throughout the life cycle, from design to material reuse.

Renewable infrastructure – including PV systems and offshore wind turbines – also requires large quantities of natural resources, such as low-carbon steel, concrete and (near) critical materials – some of which are only available in limited quantities.[7] Considering how to recover and reuse these materials at the end of design life is essential to ensure continued and equitable growth of renewable energy. Beyond opportunities for circular use of materials, there are significant safety risks at the end of life. If not properly planned for, not only old components but even the end-of-life issue itself may be exported to other parts of the world far from where those assets operated during their productive life, which are often less well equipped to deal with them, as examples from shipbreaking and floating oil and gas have proven.[8] More than 70% of obsolete ships end up in South Asia, where they are broken under rudimentary conditions on just three beaches, Alang-Sosiya in India, Chattogram (formerly known as Chittagong) in Bangladesh, and Gadani in Pakistan – a practice known as 'beaching'.[9]

Designing and decommissioning renewable infrastructure, such as solar PV and wind turbines, poses unique engineering challenges, which are broadly split across the three stages of the process:

1. **Pre-decommissioning:** hazard identification and risk assessment.

2. **Execution:** dismantling of equipment, transportation and processing of components.

3. **Post-decommissioning:** monitoring, contamination, safety, and risk management of both the site and decommissioned components.[10]

When solar systems, wind turbine components and project-related infrastructure reach the end of their design life, there are several management options to consider:[11]

1. **Extension (reduce):** A PV system or wind turbine that is not damaged at the end of its specified design life can continue to operate. For wind turbines, while many stakeholders are in favour of extension, there are many political, economic and technological challenges to overcome before the potential of extension can be fully realised.[12]

7 Critical materials: demand-side resource efficiency measures for sustainability and resilience, National Engineering Policy Centre, 2024, at https://raeng.org.uk/media/qutgamxj/nepc-critical-materials-report.pdf (retrieved 13 May 2025).
8 Safer End of Life of Offshore Wind Infrastructure, Engineering X, November 2024, at https://engineeringx.raeng.org. uk/media/hcdl42tu/engineeringx-offshore-wind-workshop-report.pdf (retrieved 13 May 2025).
9 The Problem, NGO Shipbreaking Platform, n.d., at https://shipbreakingplatform.org/our-work/the-problem / (retrieved 13 May 2025).
10 The Complete Guide to Solar Farm Decommissioning, The Solar Recycling Company, 7 January 2025, at https:// solarrecycling.com/the-complete-guide-to-solar-farm-decommissioning/ (retrieved 13 May 2025).
11 Solar PV recycling, Assereto, M., and Gilligan, C., 2021. In S&P Global. IHS Markit Clean Energy Technology.
12 "Extending the Lifetime of Offshore Wind Turbines: Challenges and Opportunities", Shafiee, M., Energies 2024 17(16), 4191, at https://doi.org/10.3390/en17164191 (retrieved 13 May 2025).

2. **Refurbish and maintenance (reuse):** Defects of the PV system or wind turbine, such as broken modules, are fixed or swapped with new modules. Maintenance becomes increasingly important as components age beyond their design life.

3. **Repower:** Typically, old components or modules are exchanged for newer modules. In some cases, the newer modules will have a higher power rating because of advanced technology, and so the total output of the PV system or wind turbine is increased. This is particularly challenging for offshore wind, where the increased size of new turbines may mean they can no longer be installed on the old foundations.

4. **Decommission:** A PV system or wind turbine that is no longer functioning is dismantled.

When the decision is made for the infrastructure to be decommissioned, this can be handled through repurposing – using components to create new products such as pedestrian bridges for wind turbines or tables for PV panels; recycling the components into new materials; or disposing of them, including landfilling, incineration or leaving in-ground components in place.[13]

Mixed raw materials and recycling

If decommissioning is the chosen path, it is crucial to consider the raw materials when determining what can be reused or recycled and what becomes waste. Solar PV modules primarily consist of crystalline solar cells (c-Si), which are made up of glass, polymers, aluminium, polysilicon, copper, and silver. The panels also include electrical and structural components such as junction boxes, connectors, cables, and the racking frame, which contain materials such as plastic, copper, aluminium, and steel. Ultimately, it is expected that 85%–90% of the module material by weight can be reclaimed during the recycling process of a c-Si module.[14]

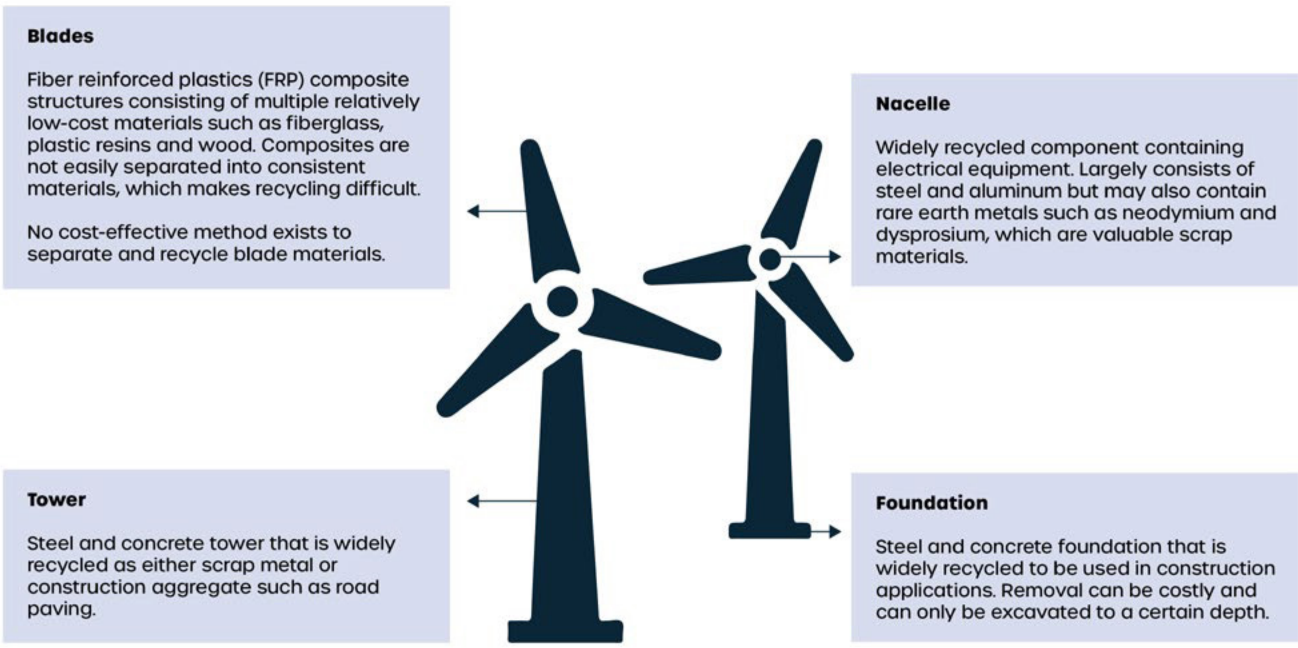
The recycling process not only poses significant safety risks due to the materials involved, but is also expensive. This is driven by factors including the need to transport modules over long distances and potential breakages; the costs of recycling, including the electrical and chemical requirements; and the need to dispose of any final waste products safely.[15]

13 Decommissioning Solar Energy Systems Resource Guide, Kolbeck-Urlacher, H., June 2022, Center For Rural Affairs, at https://www.agrisolarclearinghouse.org/decommissioning-solar-energy-systems-resource-guide-2/ (retrieved 13 May 2025).
14 "Comprehensive Review of Crystalline Silicon Solar Panel Recycling: From Historical Context to Advanced Techniques", Chen, P.-H., Chen, W.-S., Lee, C.-H., and Wu, J.-Y., Sustainability 2024 16(1), 60, https://doi.org/10.3390/su16010060 (retrieved 13 May 2025).
15 Solar PV recycling, Assereto, M., and Gilligan, C., 2021. In S&P Global. IHS Markit Clean Energy Technology.

Wind turbines consist of four primary components, each containing parts and materials that influence their end of life. While the majority of wind turbine components are presently recycled and have established practices (approximately 85% to 90% of turbine mass), the blades pose a greater challenge because of the use of composite materials (thermosetting fibre reinforced polymers), chosen for their strength and resilience, which are harder to recycle.[16]

As a result, blades are commonly disposed of in landfills or incinerated.[17] There are innovative technologies available for blade recycling, and an increasing number of companies offer composite recycling services, but these solutions have yet to become widely accessible or cost competitive.[18] However, several prototype recyclable blades have been produced and are currently undergoing pilot testing.[19]

Figure 3: Wing turbine recycling



16 "Recycling of thermosetting composites for wind blade application", Dorigato, A., Advanced Industrial and Engineering Polymer Research 2021 4(2), 116, at https://doi.org/10.1016/j.aiepr.2021.02.002 (retrieved 13 May 2025).
17 Wind Turbine Recycling Report: 2021, Sheridan, J. 2021. In S&P Global Commodity Insights. Global Clean Energy Technology.
18 See, for example, A Danish wind turbine giant just discovered how to recycle all blades, Lewis, M, Electrek, 8 February 2023, at https://electrek.co/2023/02/08/wind-turbine-recycle-blades/ (retrieved 13 May 2025), and Carbon Rivers makes wind turbine blade recycling and upcycling a reality with support from DOE, U.S. Department of Energy, 17 October 2022, at https://www.energy.gov/eere/wind/articles/carbon-rivers-makes-wind-turbine-blade-recycling-and-upcycling-reality-support (retrieved 13 May 2025).
19 Siemens Gamesa pioneers wind circularity: Launch of world's first recyclable wind turbine blade for commercial use offshore, Siemens Gamesa, 7 September 2021, at https://www.siemensgamesa.com/global/en/home/press-releases/launch-world-first-recyclable-wind-turbine-blade.html (retrieved 13 May 2025).

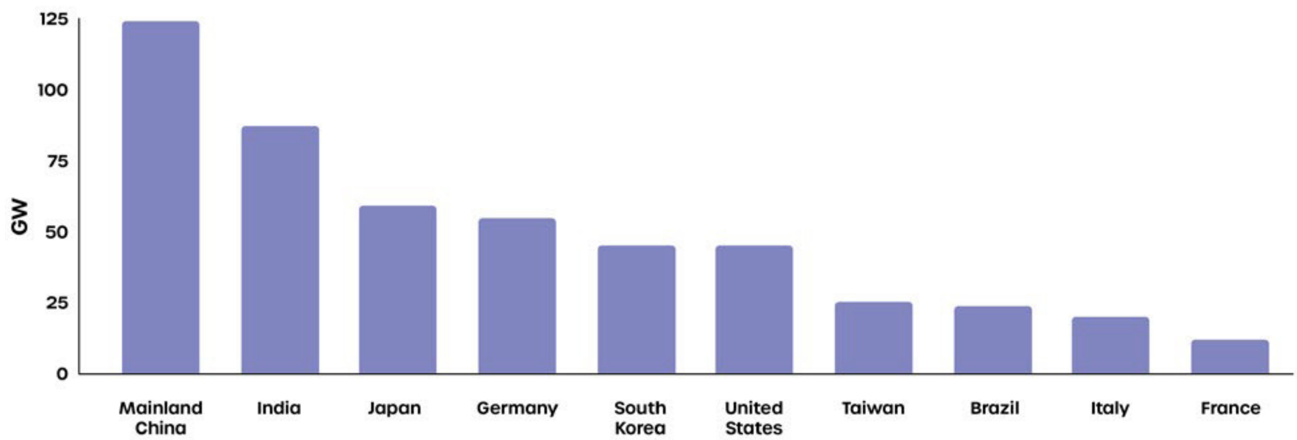
The pace of retirements

Wind capacity retirement refers to the dismantling of a wind turbine and may occur at the end of its expected lifetime or earlier because of repowering. Wind capacity retirements are projected to exceed 300 GW across Europe and North America by 2050. S&P Global forecasts that over 5 million metric tons of blades will be retired by 2050, with a virgin raw material value of £18 billion.[20]

In the solar PV sector, end-of-life management is also experiencing significant growth, with the market expected to reach £33 billion by 2050.[21] Nearly 700 GW of solar PV capacity will retire over the next three decades, with the pace of retirements picking up exponentially after 2040.[22] As the volume of decommissioned materials mounts, plant owners and governments need to establish set procedures on how to deal with solar PV end of life and decommissioning.

The rate of solar PV module retirement varies worldwide, with only 10 markets expected to make up 73% of PV retirements by 2050.[23] Recognising the unique circumstances in their own and other countries as their infrastructure retires is instrumental in shaping the decommissioning strategy implemented by local engineers.

Figure 4: PV retirements by 2050 - Top 10 markets



20 Wind Turbine Recycling Report: 2021, Sheridan, J, S&P Global Commodity Insights, Global Clean Energy Technology Reports, 8 January 2022.
21 Solar PV recycling: end-of-life management ramping up to a $33 billion market, Assereto, M., and Law, S., 2021. In S&P Global. IHS Markit Clean Energy Technology.
22 Ibid.
23 Ibid.

Decommissioning large scale infrastructure

There are crucial differences in the decommissioning of onshore and offshore wind farms. To date, decommissioning experience is mostly limited to onshore wind installations, as the first commercial-scale offshore wind farms will only reach the end of their design life from 2030 onwards. To establish safe and sustainable end-of-life processes before problems arise, stakeholders from across sectors, national borders and the whole life cycle of a wind farm must collaborate now.[24]

Decommissioning an onshore wind farm project can take from 6 to 24 months, contingent upon the scale and quantity of turbines in the project. Decommissioning projects entail the dismantling and removal of wind turbine components. Requirements may be set by national legislation or on a contract basis. For example, Italy requires operators to restore sites to their preproject state, while in Spain, any decommissioning requirements are included in the Environmental Impact Assessment.[25] This is one example of diverse regulatory requirements that would influence the engineering expertise necessary for decommissioning. In the process of land restoration, extra tasks such as land recompaction, vegetation reseeding and the replacement of damaged infrastructure would be triggered, necessitating the involvement of environmental and civil engineers.

Other significant challenges include the intricacies of transporting large components, such as wind turbine blades and tower sections, as well as material separation for the reclamation of raw materials. Moreover, transportation requirements for onshore turbines vary depending on the region and the chosen disposal method. High costs can be mitigated by using railway links for blade transportation, reducing blade dimensions before transportation and establishing inventories of blades for bulk conveyance to recycling facilities or landfills. Materials can be separated through mechanical, thermal or chemical processes, although preserving material integrity is challenging across all options.[26]

In addition to these challenges, offshore wind faces further complications due to the novelty and uncertainty regarding most aspects of its decommissioning. This includes lack of clarity on removal requirements for wind turbine foundations and cables; lack of experience with the technical removal of turbines from the seabed and transport onshore; competition between the decommissioning and construction sides, as well as with other sectors, such as offshore oil and gas, for logistical equipment such as vessels and port infrastructure; and lack of preparation from the recycling and reuse industry for the sheer volume and size of components.[27]

24 Workshop report: Safer End of Life of Offshore Wind Infrastructure, Engineering X, November 2024, at https://engineeringx.raeng.org.uk/media/hcdl42tu/engineeringx-offshore-wind-workshop-report.pdf (retrieved 13 May 2025). Engineering X is supporting efforts by convening stakeholders and raising awareness of the end-of-life challenges at the international level.

25 Decommissioning of Onshore Wind Turbines – Industry Guidance Document, WindEurope, 20 November 2020, at https://windeurope.org/intelligence-platform/product/decommissioning-of-onshore-wind-turbines / (retrieved 13 May 2025).

26 Wind Turbine Recycling Report: 2021, Sheridan, J., 2021. In S&P Global. Global Clean Energy Technology.

27 Workshop report: Safer End of Life of Offshore Wind Infrastructure, Engineering X, November 2024, at https://engineeringx.raeng.org.uk/media/hcdl42tu/engineeringx-offshore-wind-workshop-report.pdf (retrieved 13 May 2025).

What roles do industry, government and professional engineers play?

The three stakeholder groups in the ECI 2025 framework play pivotal roles in addressing the end-of-life challenges faced by renewable energy infrastructure. End of life is often not well planned, and the resulting safety implications have significant ramifications for the wider population.

Professional engineers

Professional engineers have a responsibility to consider end-of-life issues during the design and construction of equipment. These challenges necessitate the expertise, skills and services of various engineering disciplines that operate across different types of renewable energy infrastructure. This includes materials engineers, health and safety engineers, mechanical engineers, electrical engineers, civil engineers, process engineers, and environmental engineers.[28] During the recycling process, valuable materials are extracted from the renewable infrastructure. Engineers therefore require an understanding of the different extraction methods relevant to the different components, such as chemical, thermal and mechanical.

Professional engineers must learn to carefully consider end-of-life challenges and incorporate circularity into the earliest stages of the design process. In Scotland, the University of Aberdeen offers a Master of Science in Decommissioning. This programme concentrates on the crucial technical, commercial, regulatory, and environmental aspects associated with the decommissioning of energy infrastructure.[29] This type of systems perspective is vital for engineers when considering and designing the decommissioning strategy of current and future renewable energy assets.

Engineers are vital in maintaining, optimising and extending existing systems that harness energy from the sun and wind. With a growing focus on end-of-life management, engineers can also develop new, more circular solar and wind technology that can further support progress to a low-carbon future. These skills are crucial as government and industry objectives shift towards considering end of life throughout the design of the infrastructure.

28 Architecture and Engineering Occupations, U.S. Bureau of Labor Statistics. n.d., at https://www.bls.gov/ooh / architecture-and-engineering/home.htm (retrieved 13 May 2025).

29 Decommissioning, MSc, University of Aberdeen, n.d., at https://www.abdn.ac.uk/study/postgraduate-taught / degree-programmes/1015/decommissioning/ (retrieved 13 May 2025). The focus is oil rigs and offshore structures, but many of the broader issues of project management, business, law, health, safety and environmental considerations are transferrable to thinking about end of life and decommissioning for many types of energy infrastructure.

Government

It is crucial that national governments and, where applicable, regional or local authorities develop standards, policies and regulations to ensure that decommissioning is properly considered at the outset of a project and properly managed when the project reaches its end of life. Through effective policies, the government can provide incentives to boost demand for recycling services and introduce tax regulations to discourage landfill use. Public investment in recycling capacity could also help incentivise private investment. Through regulatory measures, renewable energy providers will be required to incorporate sustainable end-of-life management into the design and engineering phases to enable component recovery. An example of such a policy in action is the Photovoltaic Module Stewardship and Takeback Programme, implemented by the state of Washington in the US.[30] The programme stipulates that no manufacturer can sell PV modules unless they have also submitted a takeback or recycling plan. The manufacturer must provide an outline detailing how they intend to maximise the recovery of PV module components and ensure that at least 85% of the collected modules can be reused or recycled.

In the wind sector, France implemented new regulations in 2020 that impose specific recycling obligations for the decommissioning of wind turbines.[31] Wind farm owners are obligated to recycle a certain percentage of the wind turbine mass, with the requirement progressively increasing year by year. Additionally, recycling obligations will necessitate wind farm owners to provide evidence of recycling waste turbine materials. While this may lead to increased financial costs for decommissioning in the short term, it will stimulate the development of more recyclable turbines, recycling technology, and facilities in the long run.[32]

A note on batteries

Batteries are another crucial component of renewable energy infrastructure, playing a vital role in electric vehicles and off-grid solar systems. However, the strategies for decommissioning batteries are still in their infancy due to the early stage of the industry, so could take lessons from solar and wind decommissioning.

The increasing demand for electric vehicles is driving exponential growth in the use of lithiumion batteries. It is projected that the annual global demand for lithium-ion batteries will surge to nearly 1,700 GWh in 2030 from approximately 230 GWh in 2020. Lithium-ion batteries in electric vehicles deteriorate over time and typically come with a warranty of only eight to ten years.*

Like wind and solar infrastructure, lithium-ion batteries possess valuable raw materials that can be extracted during the recycling process. Cathode components – primarily cobalt, lithium and nickel – from end-of-life batteries can be reclaimed and reintroduced back into the supply chain to reduce demand. A diverse range of companies are poised to capitalise on the impending surge of spent lithium-ion batteries, which is expected to reach critical mass by the early 2030s.

* Battery recycling industry emerges as wave of spent lithium-ion batteries looms, Gardett, P., Hilton, G., and Karst, S., S&P Global, IHS Markit Climate and Cleantech, 2021.

30 Solar PV recycling, Assereto, M., and Gilligan, C., 2021. In S&P Global. IHS Markit Clean Energy Technol1gy.
31 Decommissioning of Onshore Wind Turbines, REGLOBAL, 30 November 2020, at https://reglobal.org / decommissioning-of-onshore-wind-turbines/ (retrieved 13 May 2025).
32 Wind Turbine Recycling Report: 2021, Sheridan, J. 2021. In S&P Global. Global Clean Energy Technology.

Engineering industry

The engineering industry has a leading role in manufacturing renewable energy infrastructure and capitalising on new opportunities that will arise from the growing decommissioning activity. For instance, there are currently prospects for decommissioned parts of wind turbine blades to be used in cement as an alternative feedstock in clinker (building material) production.[33] This will reduce the environmental impact of cement manufacturing and prevent blades from ending up in landfills. Recycling companies, in partnership with academia, can also develop cost-effective recycling solutions for wind turbines. If recycling companies can generate a valuable end-product from wind turbines, they will be in a favourable position as both onshore and offshore turbine decommissioning escalates throughout the 2030s.[34]

Industry in partnership with trade bodies, engineering associations and standards organisations can develop standards that stay up to date with the leading practices for designing and decommissioning equipment. For example, the American Clean Power Association has outlined industry recommendations for decommissioning renewable energy facilities. This includes the development of a decommissioning plan, requirements for removal and cost considerations such as the restoration of landowner property and credit for reclaiming.[35] Similarly, European trade components. association WindEurope holds a working group that has formulated industry guidance for the decommissioning and dismantling of onshore wind turbines.[36] These will contribute to the establishment of an international standard under the auspices of the International Electrotechnical Commission (IEC).[37]

Governance relating to corporate sustainability objectives will exert a lasting influence on decommissioning, through increasing the industry's responsibility for overall wind turbine life-cycle sustainability and encouraging industry involvement in recycling research and development initiatives.[38] Collaboration across the industry enables the sharing of experiences and best practices, ensuring that, in the early stages of a solar or wind project, all aspects of sustainability are considered in the context of decommissioning.

For solar PV technology, module manufacturers can consider future recyclability and circularity in upfront module design, allowing module components to be easily reused in the production chain. While the development cost is low, providing little incentive for recycling, this is an opportunity for manufacturers to get ahead of future regulatory requirements. For example, First Solar is an American manufacturer of solar panels that has its own recycling programme for its modules,

33 "Cement makers burn turbine blades as wind power faces recycling headache", Holger, D., & Petroni, G., The Wall Street Journal, 26 April 2022, at
34 Wind Turbine Recycling Report: 2021, Sheridan, J., 2021. In S&P Global. Global Clean Energy Technology.
35 Renewable Energy Facility Decommissioning: Industry Recommendations, Clark, H., American Clean Power Association, n.d., at https://cleanpower.org/wp-content/uploads/gateway/2021/01/Final_Decomissioning-Fact-Sheet_Oct21.pdf (retrieved 13 May 2025). Decommissioning of Onshore Wind Turbines, Industry Guidelines, WindEurope, November 2020, at https://windeurope.org/intelligence-platform/product/decommissioning-of-onshore-wind-turbines/ (retrieved 13 May 2025)
36 Ibid.
37 Ibid.
38 Solar PV recycling, Assereto, M., and Gilligan, C., 2021. In S&P Global. IHS Markit Clean Energy Technology.

with material recovery rates achieving 95%.[39] Supply chain infrastructure is an important industry factor to consider as renewable energy infrastructure and decommissioning projects continue to scale. Recyclability and circularity in the upfront design can stabilise the supply chain through easing the process of securing resources.[40]

Furthermore, the industry must prioritise employee training in the standards and techniques for recovering valuable end-of-life material. Engineers should undergo training provided by original equipment manufacturers on secure operations and decommissioning procedures. Partnerships between different stakeholders can also be critical. For example, in 2021, industry and academic representatives received funding from Innovation Fund Denmark for a three-year DecomBlades project, which seeks to provide the basis for the commercialisation of sustainable techniques for recycling wind turbine blades. The consortium consists of Siemens Gamesa Renewable Energy, the Technical University of Denmark, and other industry and academic institutions. These types of partnerships are key for skills development and the creation of more sustainable renewable infrastructure.

Conclusion

The intricate challenges posed by the end of life of renewable energy infrastructure cannot be meaningfully addressed without the collaborative efforts of the three stakeholder groups outlined by the ECI 2025. It is imperative for engineers to take a leading role in designing the processes and solutions necessary to meet the present and future end-of-life requirements of a world increasingly embracing renewable energy. Furthermore, it is crucial to ensure that engineers across disciplines possess the skills needed to fulfil this role, including technical skills, such as component recycling and extraction methods, as well as professional skills, such as systems thinking and the integration of circularity into the design of infrastructure from the outset. Governments and regional and local authorities have a significant part to play in increasing regulations and incentives for safer end-of-life practices and recycling initiatives for renewable energy infrastructure. The engineering industry can drive sustainable practices in the end of life of renewable energy infrastructure, from integrating circularity and end-of-life planning into the design stage to improving and expanding recycling opportunities. Through partnerships with associations and trade bodies, they can develop effective standards and practices, and through partnerships with academia, they can invest in research and skill development. The collaboration between engineers, government and industry is pivotal in maximising the potential of end-of-life practices that effectively serve the community with safety and sustainability as top priorities.

39 Wind Turbine Recycling Report: 2021, Sheridan, J., 2021. In S&P Global. Global Clean Energy Technology
40 What It Takes to Realize a Circular Economy for Solar Photovoltaic System Materials, National Renewable Energy Laboratory, 2 April 2022, at https://www.nrel.gov/news/program/2021/what-it-takes-to-realize-a-circular-economy-for-solar-photovoltaic-system-materials.html (retrieved 13 May 2025).