Sustainability Case Study with Ansys Granta EduPack

Wind Farms

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Summary

Wind farms are the fastest growing sector of the renewable electric power market. The scale of their construction creates a growing demand for materials, some of them "critical" in the sense that their supply chain is at risk. Does this threaten wind power as a future sustainable development?

This resource is divided into two sections: a handout to be used with students in the classroom and an example assessment.

*Referenced websites were accessed at the time of the last update date.

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Wind Farms-- Handout

Introduction and Background

Figure 1: an image of both on-shore and off-shore wind turbines

In 2021 Nations have adopted the Glasgow Climate Pact, collectively agreeing to work to reduce the gap between existing emission reduction plans and what is required to reduce emissions, so that the rise in the global average temperature can be limited to 1.5 degrees, in the continuum of the 2015 Paris Agreement on Climate Change. According to the International Energy Agency (IEA), electrical power generation accounted for about 34% of greenhouse gas emissions that same year. A bit more than a quarter of this power is from renewable sources – biomass, hydropower, geothermal and wind and solar. It is difficult to expand the first three – there are limits on sites and areas for biomass production. The fastest growing sectors of renewable electrical power are those capturing wind or solar energy.

In 2021, The United Kingdom has set a world leading 2030 ambition of 87% low carbon electricity generation, sending out a clear signal that it is contributing fully to the Paris agreement. The motives are to increase energy security and meet carbon reduction obligations (65% reduction in greenhouse gas emissions by 2030, net zero by 2050)[1]. Current (2022) renewable energy generation (hydro, wind, solar, biofuel) is 38.2% of total demand, which breaks down to 26.8% for wind and 4.4% for solar[2]. To achieve renewable targets, UK has aimed for 50GW of installed capacity of offshore wind by 2030.

Many nations have similar aims and strategies, encouraging the building of wind farms either onshore or offshore that feed electricity into the national grid as part of their zero-carbon strategy. According to the global wind report 2022[1], to meet the 1.5°C pathway of the International Panel for Climate Change (IPCC) wind capacity should increase from 837 GW installed capacity (2021) to 3,200 GW by 2030. This would have wind represent slightly above 15% of total power capacity. Is this a sustainable development?

Who are the stakeholders and what are their concerns? What are the materials, design, environmental,

1 https://gwec.net/global-wind-report-2022/

2 https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf

regulatory or social issues involved? To answer these questions, we need facts. Armed with those, an opinion can be formed about the impact of wind farms on Human, Natural and Manufactured Capital. Given this information, a judgment can be made of the contribution of wind farms to a more sustainable future.

Background information

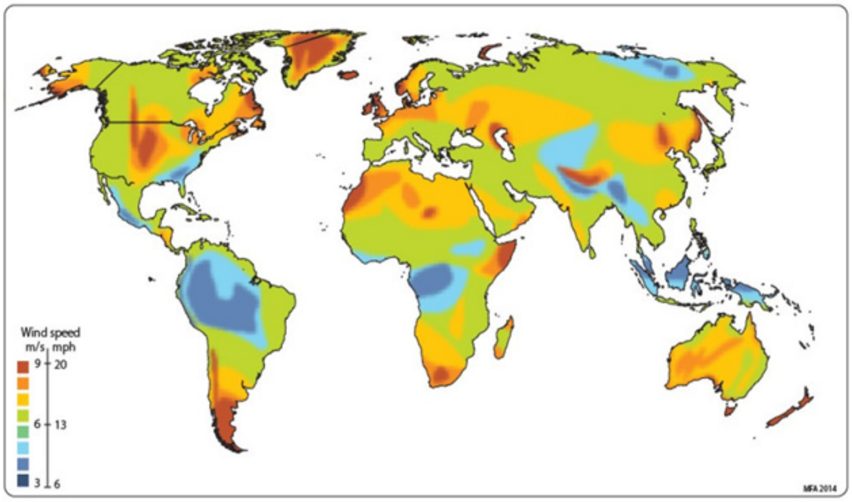

Figure 2: A global map of average wind speed

Wind turbines only produce energy when and where the wind blows (Figure 2). The ratio of the actual average power output of the turbine divided by the nominal (rated) generating capacity is called the capacity factor. It is typically 30% for on-shore and 40% for off-shore turbines with average power of 4 MW and 8MW respectively. Thus onshore turbine will produce on average 1.2MW while off-shore, would generate on average 3.2MW

Figure 3: Off-shore wind turbine construction

Most of the materials of a wind turbine are conventional: carbon steel, stainless steels, concrete, copper, aluminum and polymer matrix composites. One is exceptional. The generators of wind turbines use neodymium-boron rare-earth permanent magnets (Figure 4 and Table 1). Neodymium (also used in hybrid and electric vehicles) is classified in the US and Europe as a "critical" material. It is co-produced with other rare-earth metals, of which it forms 15% on average. Current wind technology with gearbox synchronous magnet has a material intensity of 12-51t/GW. Reaching 3,200 GW installed capacity by 2030 worldwide would imply consuming 3,500-15,000 tons of neodymium per year on average.

Figure 4: the rotor of a permanent-magnet turbine

Table 1: Main elements of wind turbine magnets- starred elements are on the critical list

Nd-B magnets	Weight (%)
*Neodymiun (Nd)	30
Iron (Fe)	66
*Boron (B)	1
*Aluminum (al)	0.3
*Niobium (Nb)	0.7
*Dysprosium (Dy)	2

Methodology

This resource follows the five-step methodology, which is simply explained below and explained in detail elsewhere[3] (see, for instance, the Active Learning Tool Kit for Sustainable Development with Ansys Granta EduPack).

- What is the prime objective? What is its scale and timing? What is the functional unit?
- Who are the stakeholders and what are their concerns?
- What facts will be needed to enable a rational discussion of the proposal?
- What, in your judgment, is the impact of these facts on Natural, Manufactured, and Social Capitals?
- Is the proposal a sustainable development? Could the objective be better met in other ways?

Where can Granta EduPack help with Fact Finding?

The **Materials data-table** has records for Steels, concrete, Glass fiber carbon composites, aluminum and permanent magnets.

The **Regulations data-table** *(Level 3 Sustainability)* includes records for regulations relating to examples of subsidies or tax credits existing for renewable energies.

The **Eco Audit Tool** allows a fast comparison of the properties, carbon footprint, embodied energy and criticality status of the materials wind turbines.

The **Nations of the world data-table** *(Level 3 Sustainability)* contains records for the environmental, economic and societal statistics of the nations from which elements are sourced.

The **Power Systems- Storage data-table** lists characteristics of electric power generating systems.

The **Elements data-table** contains records for the elements of the periodic table with fundamental properties but also scarcity and supply chain characteristics.

The **Graph facility** of Ansys Granta EduPack allows data to be plotted as property charts, annotated, and saved to Word Documents.

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Wind farms – Example of Assessment

The number of the sections corresponds to that of the 5 steps of the analysis. Granta EduPack databases help with fact-finding in ways described int he handout for this case study.

Step 1: the objective, size, time scale, and functional unit

- **Objective:** to reduce global carbon emissions and increase energy self-sufficiency
- **Size scale:** Growing currently installed capacity of wind turbines to 3,200GW which averages 300GW of newly installed every year
- **Time scale:** by 2030

Is the objective realistic? To answer that we need to know a number of things. What demands for materials will this building program create? Can they be met? By how much is the carbon footprint of electrical power from wind lower than that from fossil fuels? And will 3,200 GW of this lower carbon power make any significant reduction to global carbon emissions?

But first we must consider the stakeholders.

Step 2: stakeholders and their concerns

A proper stakeholder assessment needs direct contact with those concerned. A start can be made by exploring the press and Internet. Here are nine recent cuttings:

1. "It's official; the EU commission wants 30GW a year of new wind up to 2030" (windeurope.org, 14 July 2021).
2. "world's largest 16MW offshore wind turbine was successfully installed in East China" (Global times, June 2023).
3. "US DOE finds record production & job growth in US wind power sector" (cleantechnica.com 17 August 2022)
4. "Inverness county is the wrong place for a 15-turbine wind farm, say residents" (CBC News, 12 April 2022)
5. "UK government threatened with legal action over offshore wind farms" (Financial times, 19 April 2022)
6. "Protected species trump new turbines: how a renewables designer works around wildlife" (euronews.green 11 June 2022)
7. "Some worry New jersey offshore wind project will affect views, fishing and tourism" (Philadelphia inquirer, 15 February 2021)
8. "Oil-backed group opposes offshore wind." (The intercept, 8 December 2021)
9. "Recycling turbine blades: the Achilles heel of wind power" (euronews.com 27 June 2021)

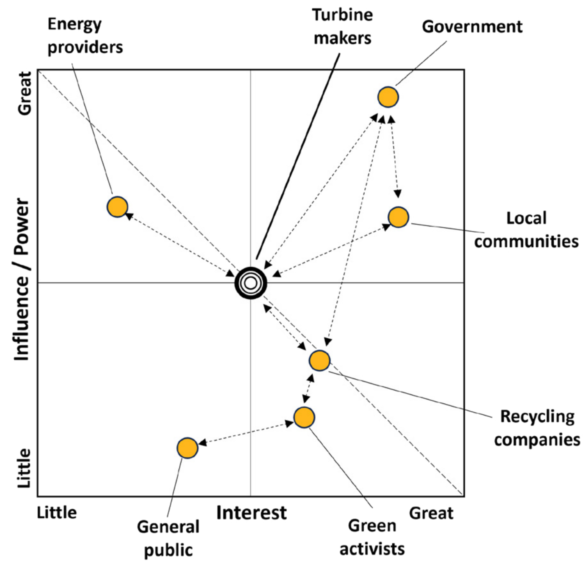


Figure 5: Stakeholders in planning a wind farm.

These headlines and the text that follows identify a number of stakeholders and their concerns (Figure 5). Among them are:

- National and Local Government. National Administrations have made commitments to reduce carbon emissions over a defined time period. They see wind farms as able to contribute, but also as a source of local wealth and employment. To encourage their construction, they subsidize renewable energy production and impose taxes on carbon emission.
- Energy providers. Carbon taxes or carbon trading schemes and carbon penalties create financial incentives for energy providers to reduce the use of fossil fuels.
- Wind turbine makers. Turbine makers want assurance that government policy on renewable energy is consistent and transparent, that incentives will not suddenly be withdrawn and that the supply chain for essential materials is secured.
- Local communities and the wider public. The acoustic and visual intrusion of wind turbines and their power- distribution system is seen as unacceptable by some, as is the danger they pose for birds or other ocean wildlife.
- Recycling companies. While 90% of a wind turbine can be recycled, there are no options available at the end of life for blades, outside of landfill or incineration.

Summary of the significant concerns

- The security of supply of the critical materials on which wind turbines depend.
- Wind farms don't reduce carbon emissions
- Wind farms are uneconomic without subsidies
- Wind farms are visually unacceptable.
- Wind farms are a danger to wild life
- Turbine blades raise landfill concerns as not recyclable

Step 3: fact finding

What information is needed to analyze the claims made for wind farms and the concerns expressed about them? What additional facts do we need for a rational discussion of the Prime Objective – that of building 300GW installed capacity per year? These questions are explored in the sections below. Figure 6 gives an overview.

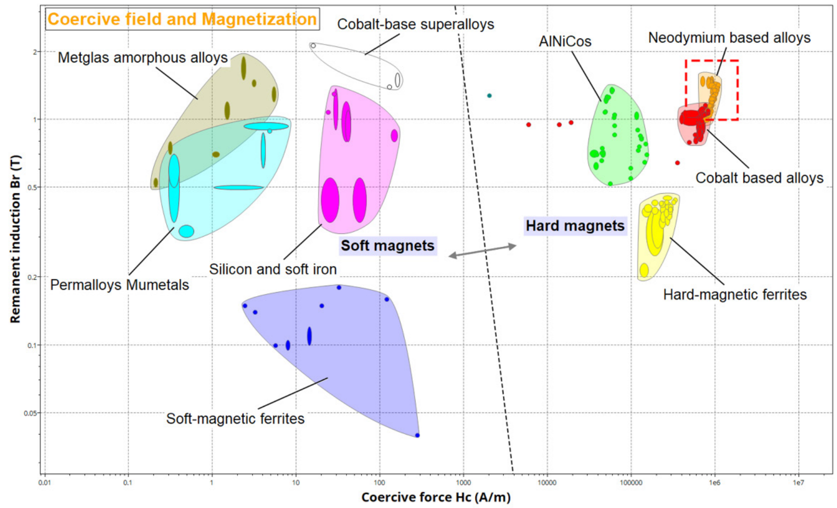


Figure 6: The remanent magnetization and coercive force of magnets, plotted from Granta EduPack 2023 R2 Sustainability Level 3 database. Nd-B magnets in red rectangle

Materials and supply chain. Among the main components of a wind turbine, permanent magnets are of highest supply concerns as they concentrate elements with high sourcing and geopolitical Herfindal Hirshman index. Permanent magnets for electric turbines require high remanent induction with high coercive field. Figure 5 shows these two properties for magnetic materials. Neodymium-based magnets (rectangle in red at the upper right) have by far the largest values of this pair of properties. If a substitute were to be sought, the next best choice would be AlNiCo or CoSm groups of magnets, but all have a smaller remanent induction and smaller coercive field. While not with the same risks, the best positioned AlNiCos and CoSms would still contain 42w% and 76w% of critical materials respectively (Aluminum, Cobalt, Samarium). Nd-B magnets are the current materials of choice for compact high-performance magnets. Neodymium is co-produced with other rare-earth metals, of which it forms 15% on average. Table 2 lists the nations that produce rare-earths and the quantities they produce[4].

Table 2: Rare earth production by Nations and Annual Quantities

Rare earth producing nations	Tonnes/year (2022)
China	210,000
United States	43,000
Australia	18,000
Burma	12,000
Thailand	7,100
Vietnam	4,300
Other	5,600
World	300,000

4 https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf

The present global production is 300,000 tonnes per year, yielding 45,000 tonnes of Nd per year. Over 70% derives from a single nation, China. Nd is listed as a “critical” material because of its uniquely desirable magnetic properties for high field permanent magnets, because its supply-chain is so narrow and because its price is volatile. The current rate of building wind turbines described in the Introduction carries a requirement of 3,500-15,000 tonnes of neodymium per year. This is 8-33% of current global production.

Materials and end of life 90% of a current wind turbine can be dismantled and recovered/recycled. The problematic components are the blades, which are typically made of glass fiber reinforced composites with either epoxy or polyester matrix. Like most composites, they cannot be recycled especially due to the matrix which are thermosets, which leaves options to downcycling (shredded and embedded in cement for example) or incineration.

Energy and energy pay-back time. Energy is used to make materials and to manufacture them into products. More energy is used transporting the products to where they will be used and assembling them to make a wind farm. Still more energy is used to connect the farm to the national grid. Numerous estimates have been made of the energy required to build and commission a wind turbine – it is of general magnitude of 650MWh per MW of nominal (rated) generating capacity.

How long will it take before a turbine has generated the energy that it took to make it?
At a capacity factor of 0.3 it will take a time t:

$$t \sim 650/0.3 = 3{,}250 \text{ hours} = 4.5 \text{ months}$$

The Environment. The Prime Objective of a wind farm is to generate electrical power with less carbon emissions than at present. It meets this objective only if the carbon emissions associated with its construction are more than offset by the low carbon emissions during life. Figure 7 compares the carbon emission per kW.hr of delivered power for alternative systems. They are approximate, but sufficiently precise to establish that wind power has the ability to generate electrical power with significantly lower carbon emissions than gas or coal fired power stations when averaged over life.

This, however, neglects power distribution: wind farms need windy places, often far from where the power will be used, and they may need energy storage systems to smooth intermittent generation.

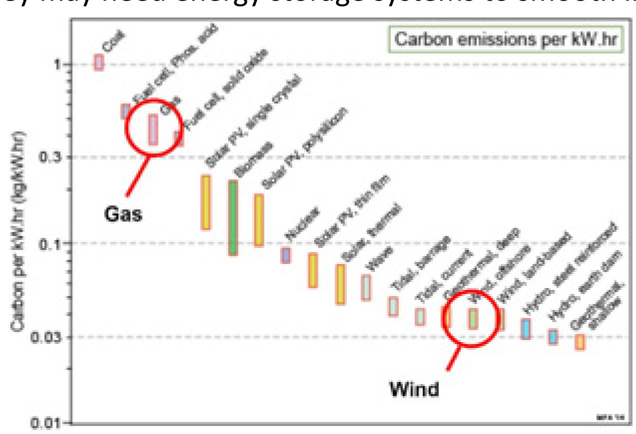


Figure 7: The carbon footprint of electrical power from coal, gas, and low carbon sources

Regulation. Much legislation across the world bears on reducing carbon emissions. They include carbon taxes, carbon trading and carbon off-setting. Making and installing wind farms initially was made financially attractive by “green” subsidies and feed-in tariffs but scaling up the production industry and advances in technology has led to Leverage Cost of Electricity (LCOE) from wind to decline by 60% over the last decade, making subsidies downgrade.

Society. The manufacture and maintenance of wind farms creates jobs. If a proportion of the revenue generated by the farm is reinvested in the local community, it can build social capital as well. Against this must be set the visual and acoustic intrusion caused by the turbines. Wind farms require a land-area per unit of generating power that is almost 1000 times greater than that of a gas-fired power station (Figure 8). To put this in perspective, if 15% of the electric power requirement of New York State (average 33 kW.hr per day, equivalent to 1.4 kW continuous per person, population 19.5 million) were to be met by wind power alone, the necessary wind farms would occupy 15% of the area of the entire State (area 131,255 km2). This is a strong reason for off-shore wind to be preferred.

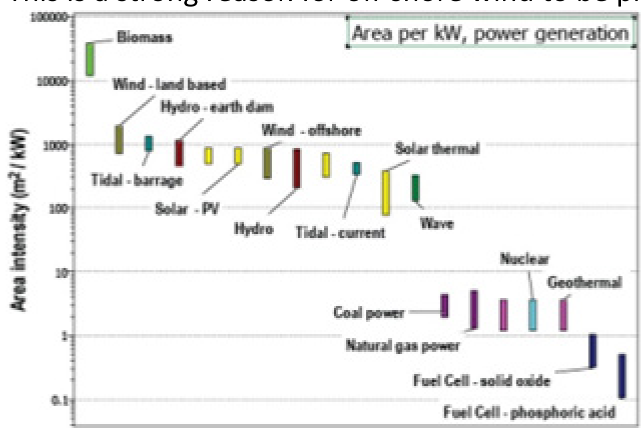


Figure 8: The area-intensity of power systems, using the Low Carbon Power data-table

Economics. Are wind farms economic? Most of the commercial-scale turbines installed today (2014) are 2 MW (nominal) in size and cost between $3 million and $4 million each . According to IRENA, with a design life of 25 years global weighted-average LCOE for onshore was $0.04/kWh in 2020, while fixed-bottom offshore wind LCOE were $0.08/kWh These values are equivalent or below gas fired stations. This, however, neglects the intermittency of wind power, which may create the need for energy storage. Grid-scale energy storage is expensive and the current state of battery technologies would add an additional burden to supply chain risks.

Summary of significant facts

- Wind power can produce electrical power with significantly lower carbon emissions than gas or coal-fired power stations
- The construction energy of a wind farm is returned as electrical energy in 4-6 months
- Compact, efficient turbines require neodymium, categorized as critical, with significant supply-chain risk
- End of life scenario for the composite blades are not satisfactory
- The cost of energy from a wind farm has significantly dropped, reaching levels or below levels that of gas or coal-fired stations. This asset is mitigated as grid-scale energy storage is needed to smooth the intermittent generation.
- Wind farms are intrusive to the communities in which they are sited. If wind farms are to contribute a significant fraction (say 15%) of energy needs this intrusion becomes widespread, hence favoring off-shore wind.

Step 4: forming a judgment

This is the moment to debate the relative importance of the information unearthed in the fact- finding step, assessing its impact on the three capitals. It will, inevitably, require an element of personal judgment and advocacy. Here is one view, summarized in Figure 9.

Natural Capital. The Prime Objective in building wind farms was to reduce green-house gas emissions. The studies cited above suggested that they can. The dependence on critical elements, particularly neodymium, for turbines, is a concern for manufacturers in non-mining countries. The placement of wind turbines being fixed and known, and large groups of them are managed by a single operator, this can be addressed by making sure their recovery, reconditioning or recycling at end of life are scheduled. Encouraging a full life cycle management of wind farm is also a way forward in dealing with end-of-life scenario of fiber composite turbine blades, which management is not satisfactory.

Injury to bird life might be dismissed as trivial when domestic cats kill far more, but this is not a productive way to respond to stakeholder concerns – a more considered response and exploration of mitigating measures (ultrasound, perhaps) is a better way forward. Impact of off-shore farms on ocean wild-life is still under study.

The beauty of the countryside is a component of natural capital. Any power-generating plant occupies space and is visually intrusive. The problem with wind farms is the scale of this intrusion if they are to contribute significantly to national needs for power. Off-shore farms reduce this problem. The long-term impact of acoustic intrusion is not known.

Manufactured and Financial Capital. The typical design-life of a wind turbine is 25 years. Building the equivalent of 300GW of turbines per year is a significant investment in energy infrastructure. Is it a good investment? Recent farm deployments have competitive or even cheaper prices than fossil plants equivalents which can be a sign to encourage future investments by banks and hedge funds. However many questions remain on grid investments needed to cope with intermittency and decentralized characteristics of wind energy. Levels of financial gains will depend on storage technology evolution (like batteries) over the next 25 years and the cost of carbon-induced climate change.

Human and Social Capital. On the positive side, large-scale deployment of wind farms creates employment. If these jobs and the wealth they generate are distributed in a fair and equitable way, a contribution is made to Human Capital. The reduction in emissions is a contribution to a healthier population. The mix of energy sources increases independence and a distributed rather than a centralized power system is more robust, harder to disrupt and less vulnerable to a single catastrophic event.

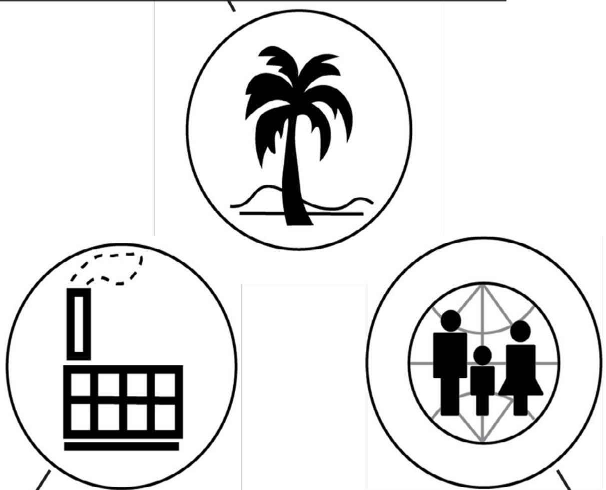
On the negative side, the visual and acoustic intrusion, already mentioned, represents to many people a significant loss of quality of life. Schemes to re-invest a proportion of the revenues generated by the wind farm in the local community in ways that help everyone, coupled with research to reduce the acoustic problem, offer a way forward.

Natural Capital

x Visually, physically and (sometimes) acoustically intrusive

✓ Provides electrical power with lower emissions than gas or coal

x Materials of some components have scarcity or recycling issues



Manufacture Capital

✓ LCOE is competitive with other energy systems, construction costs per kW.hr are projected to continue dropping by 2030

x Energy storage needed to smooth intermittent generation

x Manufacturing capacities necessary to match ambitious goals do not exist

Human and Social Capital

x Visual intrusion impacts quality of life

✓ Provides clean energy and a degree of energy independence

Figure 7. Synthesis – debating the impact of the facts on the three capitals.

Check-lists help with this and the other steps.

Step 5: reflection

Short term. The Prime Objective of wind farms – to generate electrical power with a low carbon footprint – appears to be met, making a contribution to Natural Capital. By mixing onshore and offshore farm types and stressing out local employment benefit, distribution sites can be found for them without major disruption, and the significant reduction in emissions is a positive contribution to Human Capital. While wind energy has become economic, current manufacturing capacity cannot meet the deployment pace required by nations' pledges and challenges remain when it comes to finding more sustainable materials alternatives of different parts of wind turbines, blades being one of them.

Long term. Energy is one of mankind's most basic needs and electrical energy is the most versatile and valuable form it takes. We are in transition from a carbon-powered economy to one powered in other ways but the detailed shape of the future is not yet clear. A distributed energy-mix in the economy is desirable. Recent improvements in wind technology has made its economic case stronger and no longer subsidy dependent. However the impact of the cost of energy storage needed to smooth the intermittent power from wind is still under debate. Interestingly, electric vehicles, as they become the norm, might partly solve this problem. On average a private car is used for less than 4% of the day; the rest of the day is available for charging. Introducing intelligent battery charging that draws on power when there is surplus generating capacity turns the grid itself into a virtual storage device. Accessing the critical materials needed for wind technology could be secured by using alternative magnets, and encouraging a full life cycle management of wind farm to retain them over time.

In recent reports wind is forecasted to cover up to 15% of electricity demand worldwide. Some countries like Denmark have wind providing already 50 % of power generation of the country. Enabling such large-scale shift while solving the natural, manufacturing and human challenges raised here would not be an easy task. Path to improve this could be increasing nominal capacity per turbine with new geometry design or larger off-shore blades; higher capacity factors with better operation and maintenance using Digital Twins and predictive maintenance; using innovative resins like Elium from Arkema for composite recycling at end-of life; using alternative natural based materials for towers like Modvion.

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