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Valuing the manufacturing externalities of wind energy: Assessing the environmental profit and loss of wind turbines in Northern Europe

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Abstract: This study draws from a concept from green accounting, lifecycle assessment, and industrial ecology known as "environmental profit and loss" (EP&L) to determine the extent of externalities across the manufacturing lifecycle of wind energy. So far, no EP&Ls have involved energy companies and none have involved wind energy or wind turbines. We perform on EP&L for three types of wind turbines sited and built in Northern Europe (Denmark and Norway) by a major manufacturer: a 3.2 MW onshore turbine with a mixed concrete steel foundation, a 3.0 MW offshore turbine with a steel foundation, and a 3.0 MW offshore turbine with a concrete foundation. For each of these three turbine types, we identify and monetize externalities related to carbon dioxide emissions, air pollution, and waste. We find that total environmental losses range from €1.1 million for the offshore turbine with concrete foundation to €740,000 for onshore turbines and about €500,000 for an offshore turbine with steel foundation—equivalent to almost one-fifth of construction cost in some instances. In other words, offshore turbines with steel foundations have the least environmental damage, onshore turbines are in the middle, and offshore turbines with concrete foundation the most damage. We conclude that carbon dioxide emissions dominate the amount of environmental damages and that turbines need to work for 2.5 to 5.5 years to payback their carbon debts. Even though turbines are installed in Europe, China and South Korea accounted for about 80% of damages across each type of turbine. Lastly, two components, foundations and towers, account for about 90% of all damages. We conclude with six implications for wind energy analysts, suppliers, manufacturers, and planners.

Keywords: wind energy; wind turbines; externalities; environmental profit and loss

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1. Introduction

A fair and proper evaluation of wind energy demands that we account for some of its often ignored externalities. Externalities refer to costs or benefits that result from an economic activity but are not actually priced in the economic system. We hold that the analysis of externalities is mostly neglected in the conventional approach to estimating the levelized cost of energy[1]—where the industrial sector and government research programs are focused on decisions for research investments—and rarely incorporated into how analysts and planners prioritize electricity resources or how grid operators implement integrated resource planning.[2] The analysis of externalities is sorely needed to enrich the debate on energy choices as well as to better understand the sustainability of these options. In this study, we ask: what are negative externalities associated with the manufacturing of wind turbines in Northern Europe?

To answer this question, the study draws from a concept from green accounting, lifecycle assessment, and industrial ecology known as "environmental profit and loss" (EP&L) to determine the extent of externalities across the manufacturing lifecycle of wind energy. Our EP&L cuts across the domains of manufacturing, logistics and supply chain management, environmental accounting, and corporate social responsibility and sustainability. As the Danish Environmental Protection Agency notes, "monetary valuations of environmental impacts may provide a valuable overview of the societal footprint of the business upstream activities on human welfare and also that the EP&L is a powerful method of communicating and raising awareness on the environmental and societal cost of doing business."[3] Conducting a lifecycle assessment and EP&L for wind turbines therefore enables us to make multiple contributions to the academic literature.

First, it identifies the lifecycle externalities across the supply chain for what many consider the cleanest form of energy commercially available today. One recent study concluded that wind energy is the most environmentally benign source of electricity[4] and during the 1980s the energy captured from wind turbines was understood as being completely clean without any negative environmental externalities.[5] Since then, some studies related to wind energy have begun to focus on production or operation externalities—comparing say wind with natural gas or coal[6]—or analyzing biological impacts associated with wind electricity generation such as avian mortality,[7] the death of bats striking turbine blades,[8] or social impacts such as low-frequency sounds as well as the flickering shadows produced by a turbine's blades when they come between the sun and observers.[9] We focus instead on manufacturing and supply chain externalities, an important missing gap.

Second, our EP&L facilitates identification of which parts of the supply chain have the greatest environmental impact, with an eye for improving them with better logistics management. Strategies for minimizing the extent of negative externalities can therefore be proposed and then implemented.

Third, we can look for particular configurations—such as offshore versus onshore wind—to see which have greater environmental losses. Most studies focus on only onshore wind or offshore wind, due to their separate markets and types of deployment. We, instead, do both. This can contribute to current policy discussions over which particular type of wind energy has the lowest environmental impact.

Fourth, many studies of wind energy take a geographic focus on North America or Asia, home to the two largest overall markets—China and the United States. We, however, focus on Northern

Europe, where most offshore capacity is expected to be built and where more aggressive climate and energy policies are in place to encourage renewable electricity.

2. Research concepts and methods

This section of the paper justifies our focus of wind energy, defines our key concept of externalities, and outlines the specific methods involved in the EP&L process.

2.1 Technology and case selection

We chose to analyze wind energy because it is one of the fastest growing, and cleanest, sources of electricity on the global market today and an important industry for Europe. During the past decade, investments in wind energy increased by a multiple of seven, from less than 5,000 MW installed in 2000 to more than 128,800 MW installed by the end of 2014 in the European Union.[10] More than 90 countries installed commercial wind farms in 2014. In many regions, such as Denmark or Spain, new wind installations actually operate more cheaply than conventional fossil fueled or nuclear plants.[11] Even in the United States, a heavy fossil fuel user, researchers at Lawrence Berkeley National Laboratory surveyed the actual production costs from 128 separate wind farms and found they tended to produce electricity for less than 5 cents per kWh, making them cheaper than wholesale prices for electricity.[12] Furthermore, power providers can often build the devices more quickly than larger-capacity conventional generating plants, thus enabling them to meet incremental demand growth with less economic risk, and the employment of wind energy systems diversifies the fuel mix of utility companies, thereby reducing the danger of fuel shortages, fuel cost hikes, and power interruptions, whilst meeting demand for reduced greenhouse gas emissions.[13]

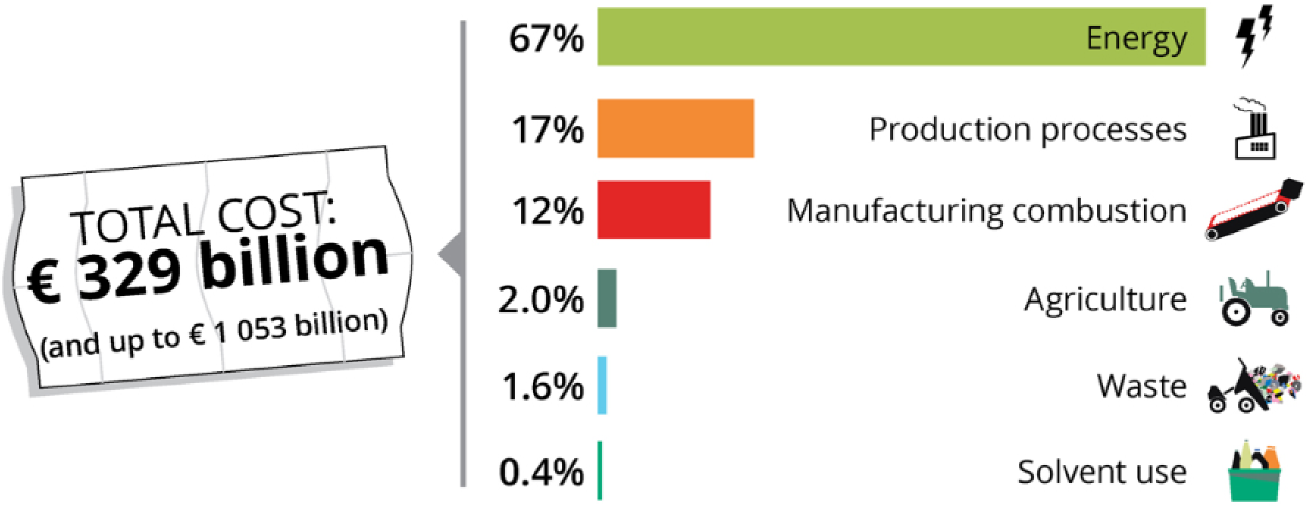
As we explain below, using logistics and supply chain data from a major European manufacturer of wind turbines, we selected one 3.2 megawatt (MW) onshore model and two 3.0 MW offshore models to examine.

2.2 Defining externalities and addressing a research gap

Externalities are “benefits or costs generated as an unintended product of an economic activity that do not accrue to the parties involved in the activity and where no compensation takes place.”[14] Externalities occur when important societal benefits and costs are "external" to, or un-priced in the marketplace. They can be negative or positive, examples being asthma from air pollution from coal-fired power plants (negative) or enhanced manufacturing competitiveness from investing in domestically made wind turbines (positive). When negative, they can be regarded as unpriced costs to doing business that befall society at large—things like pollution or the displacement of communities. One major international study conducted by the Economics of Ecosystems and Biodiversity found that the externalities associated with business practices can be shockingly large.[15] Using environmentally extended input-output modeling, that study projected that companies around the world produce $7.3 *trillion* in “unpriced” natural capital costs each year, an amount that equates to about 13 percent of global GDP. When broken down by category, most of these damages arose from greenhouse gas emissions (38%) followed by water use (25%), land use (24%), air pollution (7%), land pollution (5%) and waste (1%). When broken down by industrial or regional sector, the single largest contributor to these damages was coal-fired electricity generation.

Even in Europe and North America, where environmental regulations are more stringent than most other regions, energy industries are proving to be unruly neighbors. In the United States, two of the top sectors reporting releases to the Toxics Release Inventory—a freely accessible database that provides information on environmental pollution—are the mining and electricity generation industries, together responsible for 54% of chemical pollution.[16] In the European Union, air pollution caused as much as €1.05 trillion in damages from 2008 to 2012.[17] As Figure 1 shows, the energy industry was by far the leading source of this pollution, accounting for two-thirds (67%) of all health and environmental damages. Moreover, 50% of the damage costs were caused by only 1% of the facilities assessed, implying that a select number of companies have an immense amount of control over pollution flows.

Figure 1: Health and environmental costs of air pollution in Europe by industrial sector, 2008-2012



Source: European Environment Agency. 2014. Costs of air pollution from European industrial facilities 2008-2012 (Brussels: EEA).

Clearly, externalities need better accounted for—and a careful, systematic assessment of those attached to cleaner sources of energy, such as wind energy, are necessary for more informed, complete analysis. So far, however, such assessments have tended to be old, to focus regionally on Europe or North America rather than specifically on countries, to ignore factors beyond greenhouse gas emissions and/or to focus on operation and generation of wind electricity but not construction of the turbines.

First are those studies that are now outdated. Classic works include rigorous, extensive externality monetization studies undertaken or led in the United States by Hohmeyer and Ottinger,[18] [19] the U.S. Department of Energy,[20] [21] [22] the National Association of Regulatory Utility Commissioners[23] and the U.S. Office of Technology Assessment.[24] These studies, however, all relied on data from 1994 or earlier. The seminal European "Externalities of Energy" project (better known by its acronym ExterneE) produced a series of major reports and related publications but has not been updated since 2005, a decade ago.[25] Its methodology has also been extensively critiqued.[26] [27] [28] [29] [30] Even the comprehensive metasurvey conducted by Sundqvist, well known within the energy studies field, relied on data from 1998.[31] Innumerable changes in wind turbine siting, design, construction, and performance have occurred since these early years.

Second, given their vintage, none of these early studies ever explored to any significant degree externalities associated with offshore wind energy, nor did they investigate in-depth the externalities associated with the manufacturing of turbines in Denmark and Norway. As previously mentioned, all of the formative works from the early 1990s focused almost entirely on North America and onshore turbines, and efforts from the National Research Council to update that data has been similarly limited to the United States.[32] The ExternE studies focused generally on Europe as a region or on major energy consumers such as France, Germany, and the United Kingdom.

Third comes a slew of studies focusing only on carbon dioxide or greenhouse gas emissions, rather than other externalities such as electronic waste or noxious air pollution. Many, many studies have been performed on the greenhouse gas or carbon dioxide footprint of wind turbines or windfarms over their lifecycle.[33] [34] [35] [36] Metasurveys of this literature tend to confirm a large variation in estimated CO2 intensities,[37] and that the uncertainties in the analyses could be reduced through a standardized methodology [38] None, however, have conducted an environmental profit and loss along the contours of our study.

Lastly come those studies that explore a more holistic array of externalities, but that relate to the operation of wind farms or generation of electricity rather than their construction. The impact on public health of people living near wind turbines has been excessive debated and discussed.[39] [40] Other studies have analyzed the aesthetic or social impacts of wind energy such as flicker and shadow effects from spinning blades or disamenities caused by vibrations or noise.[41] [42] [43] [44] Still other studies have assessed the impact of wind turbines on birds and bats, [45] [46] [47] other types of environmental damage (impacts on fish or mammals, destruction of habitats), [48] [49] or disruptions to local economic activity.[50] [51] [52]

In sum, no work has yet to our knowledge provided a recent, nuanced analysis covering onshore and offshore turbines with state-of-the-art designs being manufactured in Europe with an emphasis on externalities associated with the construction phase of modern wind turbines.

2.3 Explaining the EP&L concept

In the vein of addressing this gap, we relied on the process of calculating the "environmental profit and loss," or EP&L, associated with three wind turbines. An EP&L refers to "placing a monetary value on the environmental impacts along the entire value chain of a given organization."[53] In an EP&L, the "Profit" refers to any company activity that benefits the environment, whereas the "Loss" refers to activities that adversely impact the environment. Almost all companies will have a deficit in the EP&L, reflecting the net cost to the environment.

More specifically, an EP&L involves taking the lifecycle of a given product or company, and the modeling its environmental impacts throughout the supply chain, monetizing damages, and analyzing and validating results. One report called the EP&L "an innovative and pioneering corporate approach to transparency to its environmental impact as well as a logical way to frame environmental issues for business."[54] Lankoski as similarly remarked that measuring the sustainability performance of firms is an instrumental part of doing business in the new millennium.[55]

Despite its potential, so far the EP&L concept has been only scarcely applied and utilized. The shoe manufacturer Puma[56] was the first company to ever conduct and publicly publish an EP&L in 2012 and as of early 2015 only four—from Puma (shoes), Yorkshire Water (water), NovoNordisk (pharmaceuticals), and Kerning (luxury clothing)—have been published. [57] Multiple studies have mentioned the need for something along the lines of environmental profit and loss accounting, [58] [59] [60] or summarized what Puma has done, [61] [62] [63] [64] [65] [66] [67] but no EP&Ls have involved energy companies and none have involved wind energy or wind turbines.

This lack of application is unfortunate, to say the least, given that done properly an EP&L is far more than a mere communications or publicity tool.[68] [69] It offers an important strategic tool where business planners (and logistics partners or suppliers) can better understand where they need to direct their sustainability initiatives. It offers investors and managers a risk management tool where they can minimize emerging liabilities and attempt to account for environmental damages, or benchmark themselves against other parts of the company or even other companies. It offers ordinary consumers a transparency tool they can utilize to better understand the often hidden consequences of choosing a particular product or company, making more informed choices. In sum, firms can ultimately obtain private benefits from an improved environmental performance, either by adding market value, or optimizing efficiency, to the extent where financial performance is improved, leading to what Porter has repeatedly called a "win-win" approach.[70] [71] [72]

3. Application and results

In this section of the paper, the results of our EP&L are discussed, beginning with our assumptions about location, turbine type and costs, and logistics tiers before explaining our process of externality identification (carbon dioxide emissions, air pollution, and waste) and monetization.

3.1 Location, turbine type, and costs

Primary turbine, cost, and logistics data for our EP&L come from a large European manufacturer of onshore and offshore wind turbines, whom we do not disclosure to protect confidentiality.

Due to time and resource constraints, we limited our EP&L to three state-of-the-art product types, all of similar nameplate capacity and all available commercially in 2014. In order to compare lifecycle externalities by sea and land, two offshore and one onshore turbines were chosen. The first was a 3.2 MW onshore turbine with a mixed concrete (95%) and steel (5%) foundation. The second was a 3 MW offshore turbine with a steel foundation. The third was a 3.0 MW offshore turbine with a concrete foundation. The total construction and installation cost for our onshore turbine ranged from about €3.5 to €3.7 million, the total cost for our two offshore wind turbines was about €6.6 to €6.9 million. We could have chosen larger turbines (such as cutting-edge models in the 5 to 8 MW range) but decided to stick with the 3 MW class since it remains the so-called “workhorse” of the industry and accounts by volume for more than 80% of turbine sales, for our particular manufacturer in the European market, for the past 5 years.

We selected two locations close to Denmark for deployment since it is home to the two largest European manufacturers, Vestas and Siemens Wind Power. The offshore site was located in northern Norway, and onshore site in Denmark on the island of Lolland, south of Sjælland. The Norwegian offshore project was presumed to have 45 MW of capacity in total, each turbine with 49 meter blades, with typical configuration and a location wind speeds of class IA which is the highest according to the IEC 61400 standards. Our Danish onshore project was presumed to have 33 MW of capacity with 55 meter blades in typical configuration with a wind class of IIA, according to the IEC 61400 standards.

As we explain below, we calculated equivalent carbon dioxide emissions, air pollution, and waste for nine categories of wind turbine components. We monetized these externalities into 2014€, converting foreign currencies when necessary and adjusting for purchasing power parity. We did not discount environmental damages into the future and instead set our Pure Rate of Time Preference at 0%.

3.2 Materials, logistics, and supply chain tiers

With our turbines selected, we focused on nine classes of main wind turbine components, categorized by price and sourcing relevance. These fit into the following nine categories summarized by Table 1: nacelle, generator, blade, hub, tower, power unit, transformer unit, site parts, and foundation. Materials were classified based on an ERP system with an ABC indicator, depending on their relative value. "A" materials were deemed as the "most important" parts due to their high consumption value and cost. Thus, almost all of our chosen materials have a corresponding "A" rating. In total, the components we analyzed represented less than 10% of the total number by volume (there are more than 12,000 overall from more than 500 suppliers for the particular manufacturer we collected data from) but, because we selected them strategically, about 82% to 91% of components by weight and close to 80% of components by cost.

Table 1: Nine Materials Categories for our EP&L

Category	**Inclusive of**
Nacelle	
	Main Bearing Load
	Rotor housing
	Brake disc
	Bed frame

	Fixed shaft cast
	Top box
	Rear plate
	Hydraulic unit
	Top box
	Pump unit
Generator	
	Fixed shaft cast
	Rear plate
	Brake and rotorlock bracket
	Stator plates
	Brake calipers
Blade	
	Blades
	Resin Araldite
	Hardener
	Rib laminate
Hub	
	Blade bearings
	Spinner
	Hydraulic cylinders
Tower	
	Steel plates
	Top flanges
	Middle flanges
	Bottom flanges
	Door frame
	Door
Power Unit	
	Circuit breaker
	Main/grid computer
	bundle
	Transformer
	Converter computer
Transformer Unit	
	Transformer
	Switchgear
	Cable routing
	Transformer container
	Electrical systems
	Cable set main cables
	Surge arrester
Site Parts	
	Various
Foundation	
	Steel
	Concrete

Source: Authors.

To reflect as full a range of environmental profits and losses as possible, but given real constraints in data ability and quality, we tracked the use of these materials across three different logistics tiers: (1) the sourcing process of raw materials, (2) the assembly of the modules, and (3) the transportation of the different modules to the installation site for commissioning. Our primary data was collected running a combination of transactions on the European manufacturer's ERP system.

3.3 Identifying and monetizing externalities

Naturally, externalities associated with wind energy can vary greatly by scale and scope. We selected what we considered to be the three most important, summarized by Table 2, and then calculated the environmental impact of manufacturing a wind turbine according to a series of proxies. We then further differentiated these proxies by different modes of transport, assembly techniques, waste practices, and electricity consumption patterns.

Table 2: Externality Impacts, Units of Analysis, and Proxies

Environmental impact	Proxy	Unit(s) of measurement
Climate change	Electricity consumption (kWh), kilometers travelled (by weight and distance, differentiated by sea and land)	Tons of carbon dioxide emissions
Air pollution (smog and acid rain)	Electricity consumption (kWh), kilometers travelled (by weight and distance, differentiated by sea and land)	Tons of nitrogen oxide (NO_x), particulate matter ($PM_{2.5\text{-}10}$), volatile organic compounds (VOC), and sulfur dioxide (SO_2) emissions
Waste (leachate and dis-amenity affects)	Solid waste and electronic waste (e-waste)	Tons of waste send to landfill, for incineration, and disposal costs of e-waste

Source: Authors.

We obtained kilometers travelled by sea or land data by taking the country of origin for each of the raw materials to the manufacturing plant; after the raw materials are assembled and are part of a full module (Nacelle, Blade, etc.), the calculation was made on the transportation from the manufacturing site to the specific site of installation (Denmark and Norway for this specific analysis). For electricity and kWh usage, figures were obtained directly from the ERP system, and validated internally. Waste was assessed directly from the manufacturing sites and was quantified in tons sent to landfill, for incineration, or as electronic waste (which was disposed in a separate waste stream). More details—and our specific data related to these points—are available in Appendix I: Raw Materials and Components Calculations.

To convert these specific calculations into distinct units of analysis (tons of carbon dioxide, tons of e-waste, etc.), we synthesized conversion and emissions factor data from an existing set of peer revised literature. Our idea here was to rely on replicable and publicly verifiable sours of data. Our carbon dioxide numbers for transportation (by mode, weight/volume, and distance) came from McKinnon et al. [73] and for electricity used during the manufacturing process (by country of origin) from the International Energy Agency.[74] For air pollution we used existing estimates for NO_x, $PM_{2.5-10}$, VOC, and SO_2 from the European Environment Agency,[75] Global Atmospheric Pollution Forum Air Pollutant Emissions Inventory[76], and UK Atmospheric Emissions Inventory[77] for transport and the European Commission[78] for electricity emissions factors. For waste we relied on D'Souza et al.[79], Guezuragaa et al.[80], Manwell et al.[81], and Martinez et al.[82] for incineration and landfill conversion factors and Kuehr et al. for electronic waste.[83]

To monetize these different externalities, rather than produce our own estimates and valuation techniques, we also relied on the above sources to provide us with damage estimates. We chose an average weighted value per ton of carbon dioxide of €66, €14,983 per ton of $PM_{2.5\text{-}10}$, €2,077 for SO_2, €1,186 for NO_x, and €836 for VOC. For the waste monetization rates, we used €73 per ton of waste sent to landfill, €51 per ton sent for incineration, and €110 for ton of e-waste sent for recycling and disposal. More details are provided in Appendix II: Monetization of Carbon Dioxide, Air Pollution, and Waste Calculations.

4. Discussion

As expected, the construction of wind turbines had net environmental losses—they produced more waste, or emissions, than they offset, at least during manufacturing. In aggregate, our EP&L indicates that each of the three different wind turbine types has a different, unique combination of environmental losses. As Table 3 overviews, by far the largest come from offshore turbines with concrete foundations, which had aggregated externalities (from carbon dioxide, air pollution, and waste) of almost €1.1 million—representing almost 17% the equivalent construction cost of the turbine. Offshore turbines with a steel foundation had less than half the losses—about €500,000 or 7.5% the equivalent of construction costs. Interestingly, onshore turbines had about €740,000 in losses, or 20% construction costs. These remarkable findings suggest that steel foundations results in less environmental losses and impacts than concrete foundations, even though our analysis excluded recycling. Furthermore, Table 3 reveals that environmental losses have a higher impact on onshore turbines than offshore wind turbines, due to the significant lower construction cost and fewer materials involved. This section proceeds to analyze these results in greater detail according to type of externality, location, and component.

Table 3: Summary of Environmental Losses Associated with Three Wind Turbine Types

	Offshore concrete	**Offshore steel**	**Onshore**
CO2	€	€	€

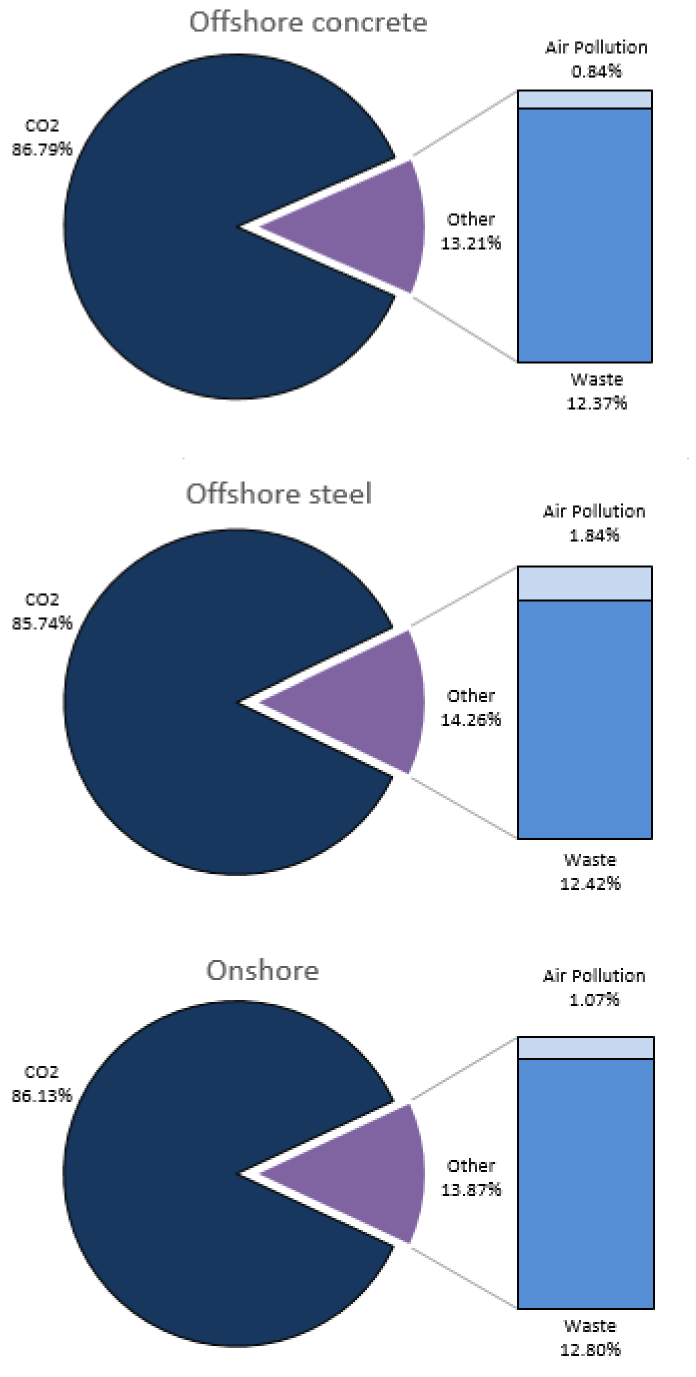
	948,694	424,490	640,086
Air Pollution	€ 9,138	€ 9,134	€ 7,956
Waste	€ 135,262	€ 61,492	€ 95,119
Total	**€ 1,093,094**	**€ 495,116**	**€ 743,161**

Source: Authors

4.1 Environmental losses by type of externality

By type of externality, carbon dioxide clearly takes the lead—by far—as the most environmentally damaging aspect of wind turbine manufacturing, and it does so across all three technology types. As Figure 2 reveals, for offshore turbines with a concrete foundation carbon dioxide represents a staggering 87% of all losses, for offshore turbines with steel foundations 85.8% of all losses and for onshore turbines 86.1%. This is because of the long distances involved between the manufacturers of raw materials, and the site location. For the two offshore turbine scenarios, 56% of the total CO_2 expenses were due to transport of raw materials on sea, and 39% due to transport of raw materials on land. For the onshore turbines, the numbers are 54% and 44%. Also, both of our offshore turbines involved combined transportation between multiple harbors, plus additional vessels that transported turbine components from harbor to site. Based on this, it is possible to conclude that most of the carbon dioxide environmental losses come from transport.

Figure 2: Distribution of Monetized Externalities by Type of Environmental Loss



Source: Authors

In addition, these figures imply that wind energy has a somewhat significant carbon debt from its manufacturing and construction. For instance, we calculate that an offshore turbine with a steel foundation involves 14,374 tons of carbon dioxide, an offshore turbine with steel foundation 6,432 tons, an onshore turbine with steel foundation 9,698 tons. With Frank projecting that every year the average 1 MW wind turbine displaces 871 tons of net avoided emissions of carbon dioxide per MW per year, a 3 MW turbine would displace 2,613 tons annually.[84] This means our offshore concrete turbine needs to work for about 5.5 years to pay off its carbon debt, our offshore steel turbine for 2.5 years and our onshore turbine for 3.7 years.

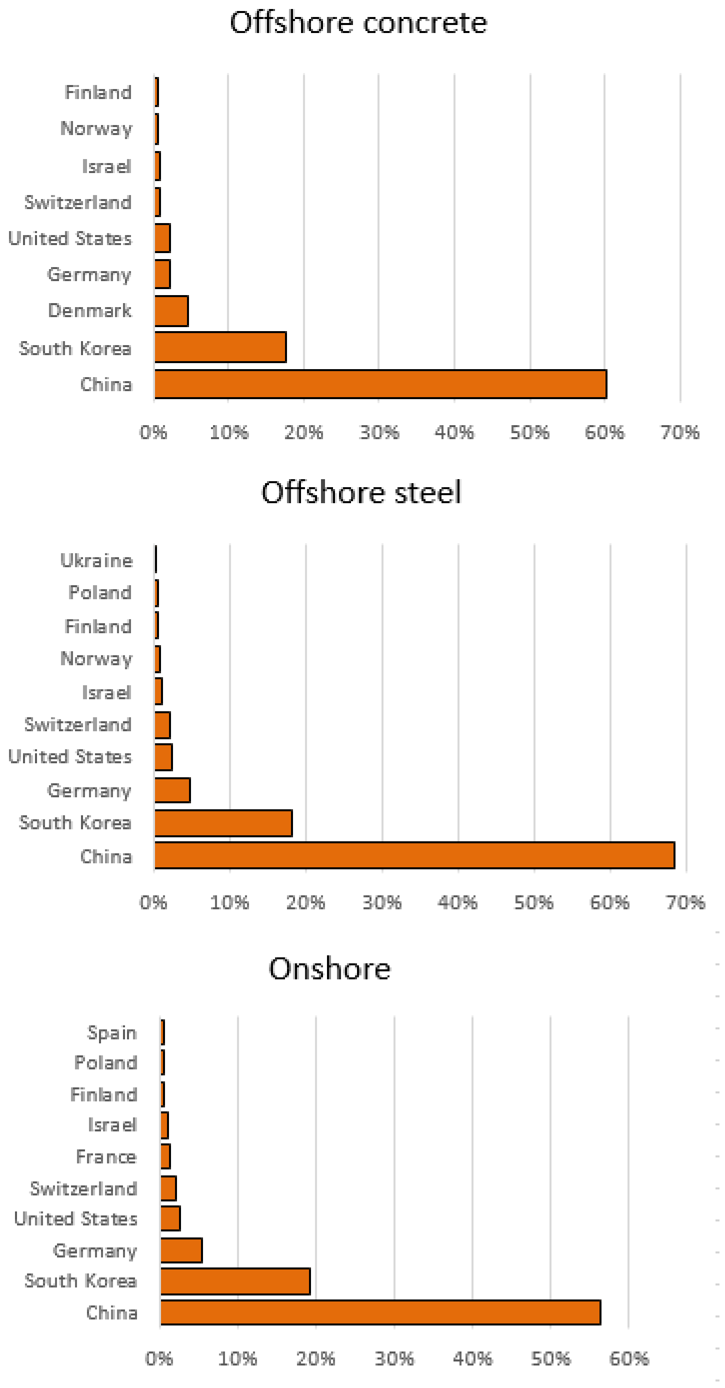
Other waste streams, notably, have a much smaller volume. Construction of our three wind turbine models produced only between 5.69 and 6.41 tons of NO_x in total, 0.05 to 0.06 tons of $PM_{2.5-10}$, 1.37 to 1.49 tons of VOCs, and 0.03 to 0.14 tons of SO_2. Similarly, concerning waste, construction of turbines produced 772 to 1,807 tons of landfill waste, 40 to 85 tons of waste sent for incineration, and about 7.3 tons of e-waste.

4.2 Environmental losses by location

The manufacturing and installation of wind turbines in Europe is still a global phenomenon given the suppliers (more than 500) and components (more than 12,000) involved. Currently, only about 10 percent of the total components for a given turbine (by volume) come from the country of commissioning. Thus, it may come as no surprise that the bulk of affiliated environmental losses with Danish and Norwegian sited turbines did not occur in Denmark or Norway. Indeed, our assessment found that for offshore concrete turbines, only about 9.2% of environmental damages occurred within Denmark and 0.7% within Norway. For offshore steel turbines, the numbers are 0.75% for Norway and 0.2% for Denmark. For onshore turbines, the numbers are 9% for Denmark and 0.1% for Norway.

Instead, as Figure 3 indicates, 60 percent of environmental damages associated with offshore concrete turbines occur in China followed by 17.5% in South Korea. Sixty-nine percent of damages for an offshore steel turbine occur in China followed by 18% in South Korea. Fifty-six percent of damages for an onshore turbine occur in China followed by 19.2% in South Korea. Clearly, these two countries account for about three-quarters (or more) of all damage across each type of turbine. One obvious explanation, connected to our discussion in section 4.1, is that these two countries supply the bulk of raw materials for turbine construction. Moreover, manufacturing facilities in these countries, especially China, are known for utilizing rather inefficient techniques for casting and forging compared to European standards.[85]

Figure 3: Distribution of Monetized Externalities by Geographic Location

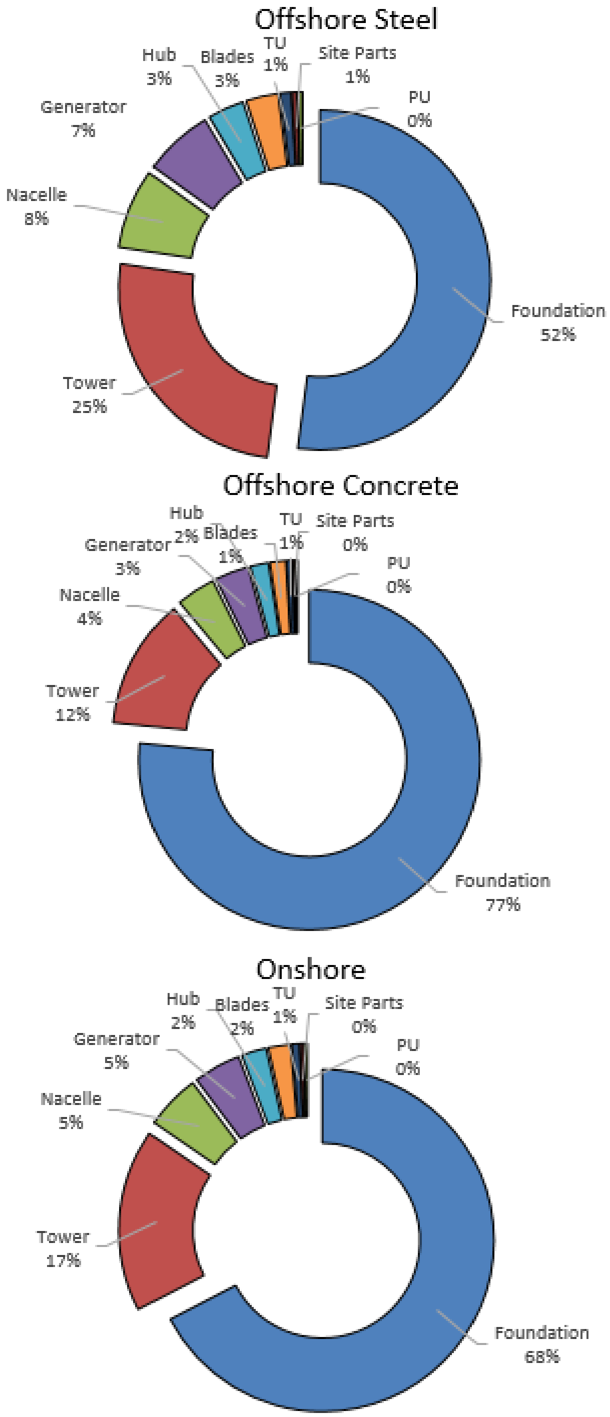


Source: Authors.

4.3 Environmental losses by component

When looked at not by type of externality or location, but specific component, another clear pattern emerges: it is the foundation that followed by the tower that accounts for most of the environmental loss. As Figure 4 reveals, more than three-quarters (77%) of externalities for a concrete offshore turbine relate to the foundation followed by 12% for the tower. For a steel offshore turbine, 52% of losses relate to the foundation followed by 25% for the tower. For an onshore turbine, 68% of losses relate to the foundation followed by 17 percent for the tower. All other components for each turbine type account for fewer than 8% of total losses and damages.

Figure 4: Distribution of Monetized Externalities by Component Type



Source: Authors.

That the foundation accounts for most environmental damage may come as no surprise given how materials intensive it is, and to how essential it is for ensuring the integrity of the rest of the structure. In the offshore wind sector, there is not even a universal platform or foundation type. Instead, a heterogeneous mix of support structures have been used in practice, ranging from monopiles, suction buckets, and gravity-based fixed bottom structures for shallow water to jackets and tripods for transitional water and floating platforms for deep water.[86] [87] Under certain conditions, an ice- breaking cone is even needed at the water surface level.[88]

Therefore, due to its material intensity, the foundation is the most damaging component for all three wind turbine scenarios. The foundation is the heaviest part of the combined wind turbine installation, negatively impacting associated CO_2 and waste costs. Much of the the steel needed for the scenarios had to be transported from China, a country prone to the manufacturing inefficiencies noted above. Concrete foundations—needed as turbines get larger in size and capacity, since more stability is required—weigh three times as much as the steel foundation, which increases their CO_2 intensity considerably, despite the fact that the concrete is produced in Denmark, and thereby closer to the site destinations.

Towers are the second most damaging component across all three wind turbine types, which, again, may be explained by its weight. After foundations, the tower is the heaviest part of the turbine, leading to affiliated environmental damage across logistics and transportation, in turn resulting in higher carbon dioxide emissions. Similar to foundations, the transport of steel from China leads to higher CO_2 costs. Also, the waste weight of the towers we examined ranged from 190 to 200 tons, and since 90% of the tower material cannot be recycled and must go to landfill for disposal, environmental losses quickly add up.

5. Conclusion

We believe our study offers six insights concerning wind energy in general.

First, despite the fact that we hold wind power to be a relatively clean source of electricity, it does have its own externalities, and these begin well before operation. Though wind likely has fewer externalities compared to fossil fuels, as Table 4 indicates it still has somewhat substantial environmental impact associated with its manufacturing and construction related to greenhouse gas emissions, air pollution, and waste. Also, from purely an environmental standpoint, offshore steel turbines have the best EP&L—the fewest losses—followed by onshore turbines with offshore concrete turbines having the worst EP&L.

Table 4: Summary of Environmental Losses Associated with Three Wind Turbine Types

Results		**Offshore concrete turbine**	**Offshore steel turbine**	**Onshore turbine**
Environmental impacts	Greenhouse gases	87%	86%	86%
	Air pollution	1%	2%	1%
	Waste	12%	12%	13%
Geographic location	China	60%	69%	56%
	South Korea	18%	18%	19%
	Denmark	9%	0%	9%
	Germany	5%	5%	6%
	United States	2%	2%	3%
	Switzerland	2%	2%	2%
	Norway	1%	1%	0%
	Others	3%	3%	5%
Component	Foundation	77%	52%	68%
	Tower	12%	25%	17%
	Nacelle	4%	8%	5%
	Generator	3%	7%	5%
	Hub	2%	3%	2%
	Blades	1%	3%	2%
	Transformer unit	1%	1%	1%

	Power unit	0%	0%	0%
	Site parts	0%	1%	0%

Source: Authors

Second, as Table 4 also reveals, across all three of our turbine types—3 MW offshore with concrete foundation in Norway, 3 MW offshore with steel foundation in Norway, and 3.2 MW onshore in Denmark—carbon dioxide emissions clearly account for most of the environmental damages, or losses. This implies that suppliers such as Siemens, Vestas, General Electric, and Suzlon need to better reduce emissions across their supply chain and also start benchmarking emissions among particular suppliers and manufacturing sites. Also, we suggest that suppliers consider transferring harbor and onsite installation manufacturing activities to the firm's facilities, to minimize emissions associated with local transport and assembly or reduce kWh consumption.

Third, foundations matter—accounting for the bulk of damages by type of component, especially concrete foundations for offshore turbines. Managing the environmental risks of foundations may require tough choices and tradeoffs to be addressed. For instance, concrete foundations are heavier and more materials- and energy-intensive, but they are also stronger, and material is sourced more locally. An offshore foundation constructed with steel weighs one-third that of concrete, but it needs transported from China, increasing logistics and transportation environmental damages. One must accept either greater environmental losses from weight versus transportation distance. Similarly, there may be a tradeoff with cost and environmental performance. European wind manufacturers could require more local sourcing of steel—cutting down its environmental losses—but this would come at a greater cost and eventually a more expensive product. Similarly, some new technologies are currently under investigation (e.g. floating foundations for offshore turbines) but remain un-commercialized and expensive. Future analysis will need to carefully assess these sorts of tradeoffs.

Fourth, recycling offers a potential strategy to manage and reduce some of the environmental losses identified in our study. Previous lifecycle analyses of large wind turbines suggests that up to 37% of the rotor, hub and blades, 90% of the tower, 47% of the site parts and 87% of the nacelle, generator, transformer and power united can be recycled, along with up to 90% of some foundation types. [89] [90] [91] [92] Drawing from these estimations, we project that anywhere from €24,000 to €53,000 of environmental losses can be offset by best practices in design, recycling, and reuse. Although this does not mitigate all or even most of the damages, it can serve to partially improve environmental performance. The implication here is that major suppliers start using and applying concepts from lean manufacturing or cradle to cradle design to simplify production flows and improve the recyclability and reuse of components.

Fifth, not only does the type of externality (carbon) or component (foundation) matter, choice of supplier is also key. Most of wind energy's negative construction externalities never befall the site location of the final turbines. Upwards of 80 of environmental losses with our three turbines were located well beyond Europe in China and South Korea. This strongly suggests that European manufacturers consider holding overseas suppliers more accountable for the environmental impacts of their components, or they analyze the possibilities of using more local suppliers to minimize logistical efforts.

Sixth and lastly, our EP&L points the way to future research. Efforts could build on our study to compare different manufacturers—we utilized data from a major manufacturing firm in Europe, but the industry features many leading companies in the United States (GE), India (Suzlon), and China (Goldwind) that would be fruitful to analyze. Comparing wind turbines cited in different geographic locations, even within the same manufacturer—conducting more site specific EP&Ls in Asia, North America, and even Africa—could reveal geographic differences in externalities. Other research could extend the EP&L beyond our three pollutants—carbon dioxide, waste, and air pollution—to include chemical pollution, degradation of land, consumptive water use, and other externalities. We've outlined a few suggestions for how manufacturers and designers can minimize externalities (through for instance local manufacturing of components with shorter transportation distances, or better attempts at recycling) but further work needs to operationalize these findings into specific and actionable recommendations. Perhaps most important, future research could compare the EP&L of wind energy with other reference classes of energy supply, such as nuclear reactors, hydroelectric dams, combined cycle natural gas fired power plants, and so on. Many of these sources of electricity are even more capital, carbon, or materials intensive than wind energy—meaning that while wind's environmental losses may look bad in absolute terms, they are actually an environmental boon in comparative terms. Without a comparative framework, it is impossible to contextualize the impact levels (both costs and benefits) from wind energy with other energy systems. We need to understand the larger picture of externalities across other electricity generation methods, since wind energy does not exist in a vacuum, and instead performs amongst a diverse portfolio of options.

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