centre for sustainable energy

Common concerns about wind power (2nd edn)

Chapter 1
Wind turbines and energy payback times

This is one of a series of chapters of evidence-based analysis drawing on peer-reviewed academic research and publicly funded studies.

For other chapters, see **www.cse.org.uk/concerns-wind-power-2017**

Centre for Sustainable Energy, June 2017

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Chapter 1
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The first edition of Common Concerns about Wind Power was published in 2011 to provide factual information about wind energy, in part to counter the many myths and misconceptions surrounding this technology.

Since 2011, much has changed in the legal and economic sphere, and a second edition became necessary. Research has been carried out for this edition since 2014. Therefore, this edition is formatted as a series of individual chapters available for download at www.cse.org.uk/concerns-wind-power-2017

All chapters written and researched by Iain Cox.

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The Centre for Sustainable Energy is a national charity committed to ending the misery of cold homes and fighting climate change.

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Chapter 1

Wind turbines and energy payback times

Summary

The harnessing of wind for the generation of electricity may rely on a renewable source of energy, but it must also prove to be sustainable. All systems for converting energy into usable forms have energy requirements themselves, where energy must be invested in the myriad activities necessary for extracting and shaping materials, transport of parts and fuel, building and maintaining power plants and associated infrastructure, and decommissioning or upgrading the site. In its very broadest sense, some even include the expenditure of capital and labour as part of the energy investment. The amount of energy involved in the manufacture, construction, operation and decommissioning of wind farms is often voiced as a concern over whether wind turbines should be used at all. Since the capture and generation of any usable form of energy requires energy to be invested, the question is really one of how effectively the generating plant returns energy back to its users (i.e. society) in relation to the energy invested.

There are a number of ways of answering this question, but all these methods essentially seek to present information in a way that is useful in understanding how society can obtain sufficient surplus energy to make its investment worthwhile. In every case, the evidence shows that wind turbines perform well in this regard, often being the most effective of the renewable energy sources after hydropower, and in most situations being comparable or superior to conventional thermal electricity generation (i.e. fossil fuel and nuclear power). Overall, wind is relatively effective – for example, modern wind farms on average return 18 times the energy invested in them over their lifetime – but specific cases have returned lower values, and many very high estimates are born of optimistic projections for electrical output or fail to incorporate certain inputs that count as invested energy. Nonetheless, the modern, larger turbines (>1 MW) typically employed in wind farms today will 'pay back' the energy invested in less than a year, in some cases in less than six months. Over the remainder of its 20 to 25-year lifespan, the wind turbine will continue to return useful surplus energy in the form of electricity back to society.

What is this based on?

Since the Industrial Revolution, the phenomenal growth and development of global society has been a story of vast surpluses of energy.[1] These surpluses have been provided by fossil fuels, and the years since the end of the second world war have seen explosive growth driven by a global economy underpinned by oil (in later years accompanied by natural gas). As readily available reserves of oil have been depleted since 1900, this glut of available energy has steadily fallen, and the energy obtained through the extraction, refinement and delivery of oil and gas fuels to where they can be used is now less than half what it used to be only four decades ago, and this downward trend will continue.[1,2]

Although global reserves of coal continue to see a healthy energy return that has changed little since the 1950s (although energetically favourable extraction is very region-specific), increasing knowledge about the profound environmental and health implications of continued coal extraction and combustion means that it is viewed as one of the least sustainable fuels. One far-reaching environmental concern is climate change, caused largely by rising levels of greenhouse gases in the atmosphere. The prodigious consumption of fossil fuels by humans has been the single largest contributing factor to rising levels of CO_2 (a major greenhouse gas), and this fact has also made the quest for alternative sources of energy even more pressing.[3]

The current dependency of the world's economy on oil and gas has prompted much debate about when these resources might run out.[2] This is not meant in the purely literal sense of there being no more oil in the ground, but instead seeks to asks when society must invest so much energy into extracting and delivering oil that the useful energy obtained is no longer worthwhile. Economic indicators such as market price and cost-benefit analysis often fail to adequately assess future resource issues, such as when depletion of a finite resource (e.g. oil and gas) means a sufficient surplus of useful energy is no longer available.[4] Even if the geological deposits do not physically run out, increased energy expenditure to extract lower-quality oil and natural gas, combined with the necessity of opening up new deposits, will entail greater environmental impacts due to resulting emissions and habitat degradation.

To get around these problems, a practical metric to describe the level of energy surplus is applied, known as energy return on investment (EROI), which measures the net energy balance of an 'energy gathering' system. Although it is a complex variable that can take into account many different factors, the basic formula for EROI is commendably simple:

$$\text{EROI} = \frac{\text{Energy returned to society}}{\text{Energy required to get that energy}}$$

At its most basic, the denominator and numerator can be expressed in the same units of energy, so giving a ratio with no units. For instance, an EROI of 10:1 ('ten to one') tells us a given process or system yields 10 joules for every 1 joule that is invested. Hence, an energy resource with a high EROI is considered a more useful or productive resource than one with a lower EROI. The EROI measurement can be a helpful indicator of the value of an energy source for several reasons. Not only does EROI provide a numerical output that can be easily compared with other energy sources, but, since it indicates the net level of useful energy that is delivered to society, it can be used as a proxy for assessing how much economic development is possible from the energy delivered, i.e. it can capture the quality of the resource.[5] This is often reflected in how useful energy is finally delivered in the system, and is one of the factors that complicates EROI analysis. Consider, for example, the delivery of a lump of coal to your house compared to mains electricity. Although both forms may contain the same amount of energy (in joules), the electricity is cleaner and more flexible at point of use than the coal; subsequently, you would be more productive consuming the electricity for your daily activities than using coal, and the greater value is reflected in the price paid for electricity.[6]

The quality aspect of EROI provides useful insights into the historical development of energy resources. Consider the typical EROI values for major energy sources given in Table 1.1. By looking at how EROI levels have changed over the course of a century, it has become increasingly clear that major fossil fuel resources are declining in quality, since EROI levels have been dropping steadily since the 1970s.[1] In the USA, which has always been one of the world's largest oil-producing nations, the EROI for a barrel of oil has declined by two-thirds since the 1970s, dropping from 30:1 to 10:1.

Natural gas data are typically aggregated with oil production, because the two energy sources are extracted from the same wells. However, data from more recent nonconventional natural gas deposits (Canadian tar sands, and 'tight gas' desposits in the USA) show a similar range of values, and a pattern of declining returns as the best resources are rapidly exploited (see Table 1.1).

The fall in EROI means that either more energy is needed to deliver a given amount of useful energy, or that the energy gain from what is currently invested is less than it used to be.[5] This has important implications for modern society, since it indicates that, despite rising prices that might drive increased exploration and extraction, or rising levels of gross production (e.g. more oil is drilled), the inevitable reduction in the quality of fossil fuels – as measured by EROI – means that these will soon no longer be viable resources to exploit as their EROI approaches a ratio of 1:1.[1,7] Even coal, which dropped from an EROI of 80:1 to 30:1 by the 1950s before returning to 80:1 in the 1990s, has only avoided this trend of declining EROI via the exploitation of lower-quality deposits that rely on cheaper surface mining. As can be seen in Table 1.1, when the value of energy is taken into account, i.e. the value of primary fuel compared to electricity, and we consider coal-powered electricity, the EROI for coal falls to less than 25:1. The detriment to climate, the environment and public health that this renewed extraction brings with it is one important factor not captured by EROI.[1]

This looming 'net energy cliff' will have a profound impact on global society. The abundance of surplus energy made available from energy sources with historically high EROI ratios has been fundamental to technological and cultural development, and maintaining EROI over a certain level is key to the improved quality of life and well-being of modern civilisation.[8] For instance, when the total energy cost of extracting and delivering useful energy to the final consumers is considered, a ratio of 3:1 EROI is calculated to be the 'bare minimum', but this would leave little surplus for other societal activities – essentially, much of society would be invested in helping deliver this energy and to maintaining fundamental services like the growing and transportation of food.[4,8] The threshold for maintaining greater well-being and quality of life (as measured by a combination of indices, such as the Human Development Index, health expenditure, and female literacy rates) is estimated to be in the range of 20:1 to 30:1 EROI. It is interesting to note that the upper value (30:1) represents a 'saturation point' above which additional surplus energy offers no further improvements to society.[8] This is perhaps an indication of how profligate many modern societies have been with their historically high rates of fossil fuel consumption over the course of the previous century, when energy was abundant and, seemingly, never-ending.

In the case of wind power, the energy investment includes: manufacturing and transporting wind turbine components; constructing, connecting, operating and maintaining the wind turbine facility (this may be multiple turbines on a wind farm); and the final decommissioning of the site and recycling of the used

Table 1.1 A range of illustrative EROI values for various energy carriers, divided between primary fuels (unshaded) and electricity (shaded).

Energy carrier	Average EROI, i.e. *x*:1 ($energy_{out}/energy_{in}$)	Comments
Primary fuels		
Oil	35	Global average
Oil & natural gas	30 11–18 10.1	U.S. domestic production in 1970s U.S. domestic production by 2005 U.S. domestic production by 2010
Natural gas	38 20 30	Canada domestic production 1993 Canada domestic production 2009 U.S. domestic production 2005
Shale oil	5	Conventional oil derived from shale formations. Initial high EROI values from U.S. extraction in the 1990s declined rapidly once 'sweet spots' were depleted
Tar sands crude oil	2–5	Note that low EROI of tar sands will lower average of oil and gas industry as a whole
Oil shale	1.4	Oil shale is a low-grade oil precursor, not to be confused with 'shale oil'
Electricity		
Oil-fired electricity	3.7–10.6	Higher value based on oil EROI of 30 (see oil & natural gas above)
Coal-fired electricity	12.2–24.6	Note EROI for coal alone (80:1) not included as it has limited use without further energy conversion
Nuclear-powered electricity	5–15	May be underestimated due to outdated processes studied
Wind-powered electricity	**18–20**	Data from meta-analysis of global wind farm installations. Larger modern turbines have higher EROI values
Solar p.v. electricity	6–12	Covers several types of modern photovoltaic (p.v.) systems. Generation based on average insolation for southern Europe
Hydropower	84	By far highest EROI with some values reported above 100, but resource geographically constrained

Figures derived or calculated from data in references 9, 15, and 16. The final EROI for solid fuels used to generate electricity or heat are based on well-head, mine-mouth or farm-gate values multiplied by typical thermal conversion efficiencies of primary energy inputs. In contrast to all renewable energy sources, fossil fuels and nuclear power use entirely non-renewable sources of energy both upstream and at point of use.

components.[9] Note that the energy invested in the wind turbine and associated infrastructure is a mix of primary energy inputs and energy carriers. What this means is that primary energy inputs, such as oil, gas or coal, have been used alongside forms of energy, e.g. such as refined oil products and electricity, that themselves have been converted from primary energy inputs. For example, primary energy inputs (combustion of coal) may be used in heat-intensive processes like steel manufacture, whereas electricity may be used elsewhere in the supply chain in the manufacture of aluminium or to operate machinery during assembly.[1]

These primary energy conversions are another key complicating factor in energy ratio calculations, since the energy inputs have differing values depending on whether they are primary fuels or energy carriers (like electricity) that themselves are the result of energy conversions.[5] Each conversion step will require an energy investment, and accounting for these energy balances in a meaningful way in relation to the final useful energy delivered is very important. Of particular relevance to renewable energy systems is the fact that the energy gathering process itself consumes some of the energy being extracted, i.e. the system needs energy to make energy.[10] This 'autocatalytic' nature of energy generation (a product of the process is used in the process itself) means that the mix of energy types invested in a power plant assume great importance if it is a source of renewable energy. For example, if the EROI is lower than the 3:1 minimum mentioned above, then the renewable energy system is effectively being subsidised by fossil fuel consumption rather than creating a surplus of renewable energy itself.[4] This is clearly counterproductive if the aim is to have a sustainable (and low-carbon) means to generate energy.[5]

There are two important points to consider when assessing the net energy return for wind power. First, wind turbines generate electricity only. As we have seen, electricity is a high-value form of energy in terms of its usefulness to society.[5] The EROI equation can be written more specifically for a wind turbine, since it is producing a high value energy carrier from primary energy inputs invested:

$$\text{EROI} = \frac{\text{cumulative electricity delivered to society}}{\text{primary energy inputs invested}}$$

One can see that if, for instance, the primary energy inputs to generate electricity in the manufacturing process could be reduced due to greater deployment of renewable electricity generation (e.g. from wind turbines already operational), then the EROI will be improved. Remember, of course, that the EROI does not account for other benefits, like large reductions in greenhouse gas emissions and other pollutants due to displacing coal-fired electricity.[1] However, many studies also report energy investments as primary energy inputs, although wind turbines will return energy in the form of electricity only.[11] Because of this, the issue of whether the energy cost of wind turbines should be adjusted to electricity equivalents is still debated, and serves to illustrate the complexity of defining energy flows in national energy infrastructures.[10,11]

The other consideration is during the operational lifetime of the turbine, where the input of energy (wind) that generates the energy output (electricity) requires no further 'gathering' once the turbine is in place.[12] This means that the vast majority of the energy investment for wind power is an upfront cost.

Rather than calculate the return over the lifetime of the power plant, which EROI measures, it is often useful to look at how soon the operating plant 'pays back' the energy invested in it – the energy payback time or (EPT).[13,14] Note that EPT can be related to EROI, but they are not interchangeable. The EROI is time dependent – whether you run your wind turbine or coal-fired power station for two or 20 years makes a big difference to how much energy the plant will generate over its lifetime, whereas it will require the same energy investment to build and decommission it regardless. In the case of a fossil fuel-fired plant, however, the lifetime also makes a big difference to the amount of fuel that needs to be extracted and delivered for conversion to electricity.

The energy flow for a wind turbine is neglible by comparison since the wind is 'free', so once the energy invested in building, operating and decommissioning is paid back, the energy delivered to society as electricity is a net gain.[12] This is why EPT is often used as a measure of how efficient renewable energy sources are, because the initial energy payback period is all that needs to be accounted for, after which point the turbine returns energy until the day it is shut down.

Once we know the EPT for a wind turbine, we can relate it EROI by accounting for the lifetime of the plant.[14] The EPT measures how long it takes to 'replace' the energy embodied in the wind turbine (including decommissioning), so we can simply take EROI to be equal to the operational lifetime divided by the EPT:

$$\text{EROI} = \frac{\text{lifetime in years}}{\text{EPT}}$$

What is the current evidence?

There are a wide range of values for EROI and EPT that have been found for wind turbines around the world. A recent report by the IPCC, based on published literature reviews that had amassed data from many operational and projected wind turbines, found that EROI values ranged from 5:1 to 40:1, and EPT ranged from as little as five or six weeks up to one-and-a-half years (the typical lifespan of the turbine was 25 years).[13] There are several issues with arranging so much disparate data from turbines together, and it is not surprising that these values exhibit a wide spread.

One of the most fundamental issues with any EROI analysis, whether fossil fuel or renewable energy system, is that of boundaries.[15] Establishing system boundaries clearly is the most important part of a net energy analysis, and it can be difficult to meaningfully compare EROI values for different energy resources if different direct and indirect energy costs are included or excluded.[5] For instance, a meta-analysis of published EROI studies encompassing data from 114 wind turbine projects found EROI values ranging from 1:1 up to a (somewhat astonishing) 126:1; such a wide spread, the authors argued, is due to the subjective nature of the boundaries set by the investigators, which omitted certain indirect energy costs.[9] The average EROI for all turbines was 25:1, but when only operational data was included this fell to 20:1. On the other hand, much of the data was derived from old, small turbines that are not indicative of modern turbines that have capacities of several megawatts. The same meta-analysis demonstrated a clear relationship between increasing turbine size and higher EROI values.[9] A different study that analysed figures published for 26 wind turbines of varying sizes also arrived at a mean EROI of 20:1.[16] Most studies agree that the global EROI average for wind power is currently 15:1 to 20:1 for turbines that have a 20 to 25-year operational lifetime.[9,13–16] Moreover, the general data trend suggests that the EROI is steadily improving as more and more newer, larger wind turbines come online, including large offshore arrays.[9,14,15]

Some published studies have reported EROI values in excess in of 30:1, which, given performance capabilities for wind technology currently, or soon to be, deployed, are likely to be optimistic scenarios for planned turbines that assume favourable capacity factors (see chapter 4, 'Efficiency and capacity factors of wind turbines') or reflect wind farms located in areas that have higher than average wind speeds.[17] This issue has been highlighted by several researchers, and it is worth remembering that the EROI is generally downgraded when real operational data is used alone (viz. the change from 25:1 to 20:1 above).[1,9] Real-world data also tends to incorporate wider system boundaries, as mentioned above, and more stringent application of energy costs due to associated infrastructure and buffering capacity (see chapter 5, 'Intermittency of wind turbines') tends to result in lower EROI ranges.[9,16,17] This issue is also evident in published assessments of nuclear power, as it is claimed that unrealistic assumptions concerning reactor performance and uranium enrichment can lead to under- or overestimates of EROI.[14,17] Looking further 'upstream' in the nuclear supply chain, it can also be seen that mining and processing are important contributing factors to nuclear power's overall primary energy input.[18] The decreasing quality of global uranium resources is likely to have an increasing impact on the energy inputs required to extract this fuel at the level required to satisfy future global nuclear expansion.[19] This introduces a certain element of risk when relying on nuclear power to supply a large proportion of future carbon savings, because a significant increase in primary energy inputs will have a subsequent knock-on effect of increasing GHG emissions.[18]

Given the context of replacing electricity generated from non-renewable sources, it is instructive to compare the performance of wind turbines with conventional and other alternative energy sources. Illustrative values are shown in Table 1.1. As can be seen from Table 1.1, EROI values for fossil fuels have steadily declined over the last century, in contrast to wind power, which, as we have seen, tends to improve as larger, more modern turbines come into operation. Data over time show that the decline seen with fossil fuel resources can be surprisingly rapid, as can be seen from values for oil and natural gas deposits in the USA and Canada (see Table 1.1). Despite the promise of new, unconventional sources of fossil fuels – tar sands oil, shale oil and dry ('tight') natural gas – many recent fields that were initially highly productive have already apparently passed their peak.[1,6,16]
Finally, relating the EROI of wind power to EPT suggests that wind turbines on average will pay back their energy investment in a little over five months.[13] The authors of Kubiszewski et al. found that EPT for turbines between 0.5 and 1.5 MW in size ranged from 95 to 193 days (i.e. roughly three to six months); operational data alone suggested EPT is slightly more than four-and-a-half months.[9] However, it is worth bearing in mind that the wind turbines in question had relatively high EROI values, and it is likely some assumptions were made in the reports analysed that excluded indirect energy inputs. Another review of 20 published studies suggested similar ranges for EPT, quoting a median (note, not the mean) of roughly five-and-a-half months, with a spread of 3.4 to 8.5 months.[20] Other recent values for large turbines (3.0–4.5 MW) give an EPT of seven to ten-and-a-half months.[11] The author of this review also points out that EPT would be extended if the primary energy invested had to be paid back in electricity equivalents, although this 'worst case' scenario would entail an EPT of roughly 20 months over the course of a 25-year operational lifetime.

Conclusion

Wind turbines are capable of generating low-carbon, high-value electricity by harnessing the natural energy flow provided by wind. Before such a energy gathering system can become operational, however, there is an energy 'cost' that is involved, because the manufacture and transport of components, site construction, operation and maintenance, and the ultimate decommissioning stage, all require energy to be invested. The value of a generating system is how much useful energy is returned to society. This can be expressed via the ratio of energy return on energy invested (EROI), although this deceptively simple equation hides a great deal of complexity. Generating systems are embedded in the wider energy infrastructure, which encompasses, at its widest, energy investments made at all stages of extraction, transport, conversion and delivery of energy in various forms. Historically, the extraction of fossil fuels has delivered abundant energy surpluses (high EROI values), but these have steadily declined as the most readily available resources have been depleted.

The non-sustainable nature of conventional energy generation, coupled with the far-reaching negative effects their use has on the environment and public health, has made the need to find alternative, renewable sources of energy particularly pressing. Maintaining the present level of development in modern society has been estimated to require a certain 'bare minimum' level of EROI for any energy resource, estimated to be 3:1. For civilisation to enjoy the full benefits of technological and cultural development that have characterised developed countries in the modern age requires a higher level, in the region of 20:1 EROI, unless society is willing to reduce present levels of consumption and use what energy is available more efficiently.

Wind power is able to offer an EROI level comparable, even superior, to present-day conventional generating systems. Existing operational data suggests an average EROI for wind of 18:1 to 20:1, and the increasing prevalence of larger, more modern turbine designs is likely to raise this average in the future. By comparison, present-day oil and natural gas resources have EROI values between 10:1 and 18:1 (Table 1.1), and industry trends means these values are likely to decline, even when taking newly exploited resources in North America into account. Coal has a higher global average of 28:1. It is noted that open mining in certain regions has seen the EROI for coal return to historically high levels (80:1), although these are lower-quality resources and involve significant environmental impacts. Typical values for nuclear power suggest an EROI of between 5:1 and 15:1, although some argue that this relies on older data that does reflect more modern techniques. The mining of uranium is essential for the nuclear industry, and thus it uses a non-renewable fuel supply chain that will become more and more depleted similar to the history of fossil fuel extraction.

Because renewable energy sources like wind rely on natural energy flows, almost all of society's energy investment is considered an upfront cost. Hence, a useful indicator of the efficiency of wind turbines is the energy payback time (EPT), which is the time it takes for a turbine to supply an amount of energy equal to the energy embodied (or invested) in it. It is important to remember that EROI and EPT are related, but not directly interchangeable. Published studies on typical modern wind turbines (capacities of 0.5 to 4.5 MW) show the EPT ranges from as little as three-and-a-half months to just over ten months. A wind turbine has an operational lifetime of 20–25 years, which means it will take just one to four per cent of its lifetime to repay the energy invested in it. Over its lifetime, a modern wind turbine would be expected to return at least 20 times the energy invested in it as renewable electricity.

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