**Technical assessment for**

**Offshore Wind Turbines**

Sector: Electricity generation

Agency Level: Utilities

Keywords: Wind Energy, Electricity Generation, Grid, Renewable Energy Source

Version 3 (June 2020)

**Prepared by:**

Abdulmutalib Yussuff, research fellow

João Pedro Gouveia, Senior Research Fellow



[info@drawdown.org](mailto:info@drawdown.org) [www.drawdown.org](http://www.drawdown.org)

Table of Contents

[List of Figures 4](#_Toc18619497)

[List of Tables 4](#_Toc18619498)

[Acronyms and Symbols Used 5](#_Toc18619499)

[Executive Summary 7](#_Toc18619500)

[1 Literature Review 8](#_Toc18619501)

[1.1. State of Offshore Wind Energy technologies 8](#_Toc18619502)

[1.2. Adoption Path 10](#_Toc18619503)

[1.2.1 Current Adoption 10](#_Toc18619504)

[1.2.2 Trends to Accelerate Adoption 11](#_Toc18619505)

[1.2.3 Barriers to Adoption 11](#_Toc18619506)

[1.2.4 Adoption Potential 12](#_Toc18619507)

[1.3 Advantages and disadvantages of Wind Offshore 16](#_Toc18619508)

[1.3.1 Similar Solution 16](#_Toc18619509)

[1.3.2 Arguments for Adoption 16](#_Toc18619510)

[1.3.3 Additional Benefits and Burdens 17](#_Toc18619511)

[2 Methodology 20](#_Toc18619512)

[2.1 Introduction 20](#_Toc18619513)

[2.2 Data Sources 21](#_Toc18619514)

[2.3 Total Addressable Market 23](#_Toc18619515)

[2.4 Adoption Scenarios 24](#_Toc18619516)

[2.4.1 Reference Case / Current Adoption 24](#_Toc18619517)

[2.4.2 Project Drawdown Scenarios 24](#_Toc18619518)

[2.5 Inputs 25](#_Toc18619519)

[2.5.1 Climate Inputs 25](#_Toc18619520)

[2.5.2 Financial Inputs 26](#_Toc18619521)

[2.5.3 Technical Inputs 28](#_Toc18619522)

[2.6 Assumptions 29](#_Toc18619523)

[2.7 Integration 29](#_Toc18619524)

[2.8 Limitations / Further Developments 30](#_Toc18619525)

[3 Results 31](#_Toc18619526)

[3.1 Adoption 31](#_Toc18619527)

[3.2 Climate Impacts 32](#_Toc18619528)

[3.3 Financial Impacts 34](#_Toc18619529)

[4 Discussion 36](#_Toc18619530)

[4.1 Limitations 36](#_Toc18619531)

[4.2 Benchmarks 37](#_Toc18619532)

[5 References 39](#_Toc18619533)

[6 Glossary 49](#_Toc18619534)

# List of Figures

[Figure 1.1 – Offshore wind capacity adoption projections in 2DS and B2DS scenarios (Adopted from IEA ETP, 2017) 13](#_Toc23609245)

[Figure 1.2 – Offshore wind electricity generation projections in 2DS and B2DS scenarios (Adopted from IEA ETP, 2017) 13](#_Toc23609246)

[Figure 1.3 – Wind Power capacity long term market projections until 2030 (Adapted from Greenpeace, 2015) 15](#_Toc23609247)

[Figure 3.1 World Annual Adoption 2015-2060 32](#_Toc23609248)

[Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction (2015-2060) 34](#_Toc23609249)

# List of Tables

[Table 1.1 Wind energy solutions comparison to conventional electricity generation technologies 18](#_Toc535272075)

[Table 2.1 Climate Inputs 25](#_Toc535272076)

[Table 2.2 Financial Inputs for Conventional Technologies 27](#_Toc535272077)

[Table 2.3 Financial Inputs for Solution 27](#_Toc535272078)

[Table 2.4 Technical Inputs Conventional Technologies 28](#_Toc535272079)

[Table 2.5 Technical Inputs Solution 28](#_Toc535272080)

[Table 3.1 World Adoption of the Solution 31](#_Toc535272081)

[Table 3.2 Climate Impacts 33](#_Toc535272082)

[Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq 33](#_Toc535272083)

[Table 3.4 Financial Impacts 34](#_Toc535272084)

[Table 4.1 Benchmarks 36](#_Toc535272085)

# Acronyms and Symbols Used

* AMPERE – Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
* BNEF – Bloomberg New Energy Finance
* CO2 – Carbon dioxide
* DOE – Department of Energy
* DS – Degree Scenario
* EDPR – Energias de Portugal - Renováveis
* ETP – Energy Technology Perspectives
* EU – European Union
* EWG - Energy Watch Group
* EV – Electric Vehicle
* GEM-E3 – General Equilibrium model for Economy, Energy and Environment
* GHG – Greenhouse Gases
* Gt – Gigatons
* GW - Gigawatts
* IEA – International Energy Agency
* IEEJ – The Institute of Energy Economics, Japan
* IMAGE/TIMER – Integrated Model to Assess the Global Environment/The Targets IMage Energy Regional model
* IPCC – Intergovernmental Panel for Climate Change
* IRENA – International Renewable Energy Agency
* LCA – Life Cycle Assessment
* LCOE – Levelized costs of electricity
* LUT - Lappeenranta University of Technology
* MESSAGE-MACRO – Model for Energy Supply Strategy Alternatives and their General Environmental impact with macroeconomic feedback
* NDC – Nationally Determined Contribution
* O&M – Operation and Maintenance
* PPM - parts per million
* PV - Photovoltaics
* R&D – Research and Development
* RES – Renewable Energy Sources
* US – United States
* USD – United States Dollar
* TAM - Total Addressable Market
* TWh - Terawatt-Hours
* VRES - Variable Renewable Energy Sources

# Executive Summary

Project Drawdown defines *wind turbines (offshore)* as: offshore utility-scale wind power technologies. This solution replaces conventional electricity-generating technologies such as coal, oil, and natural gas power plants.

Offshore solutions are increasingly being adopted where wind is less intermittent and the turbines can harvest more energy. Since the amount of power generated by a wind turbine is primarily determined by its size and the intensity of the wind resources, offshore locations are a growing and attractive prospect for wind power. By middle of 2018, the global cumulative installed offshore wind capacity was approximately 19GW with Europe and China holding 84% and 16% shares respectively.

The total addressable market for wind turbines (offshore) is based on projected global electricity generation in terawatt-hours from 2020-2050, with current adoption in 2018 estimated at 0.27 percent (i.e. 62 terawatt-hours) of generation. Impacts of increased adoption of wind turbines (offshore) from 2020-2050 were generated based on three growth scenarios, which were assessed in comparison to a Reference Scenario where the solution’s market share was fixed at the current levels. Project Drawdown Plausible Scenario is based on the evaluation of four optimistic scenarios from IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Equinor (2018) Renewal Scenario; using a medium growth trajectory, while capturing 4.2 percent of the electricity generation market share in 2050. Drawdown Scenario follows the same sources and scenarios but considering a high growth. Optimum Scenario is based upon three 100% RES scenarios of electricity generation by 2050, being Greenpeace (2015) Advanced Energy [R]evolution Scenario; Ram *et al.* (2019) scenario and Ecofys (2018) 1.5ºC scenario with a medium growth,  resulting in a 5.8 percent share of the market in 2050.

Through the process of integrating wind turbines (onshore and offshore) with other solutions, the total addressable market for electricity generation technologies was adjusted to account for reduced demand resulting from the growth of more energy-efficient technologies, as well as increased electrification from other solutions like electric vehicles and high-speed rail. Grid emissions factors were calculated based on the annual mix of different electricity generating technologies over time. Emissions factors for each technology were determined through a meta-analysis of multiple sources, accounting for direct and indirect emissions.

For offshore wind, growing from current adoption to 4.2 percent could avoid 10.8 gigatons of GHG emissions in the *Plausible* scenario. At a cumulative cost of $1.4 trillion, offshore wind turbines can deliver net operating savings of $324.4 billion over three decades of operation (2020-2050). These are conservative estimates, however. Costs are falling annually and new technological improvements are already being installed, increasing capacity to generate more electricity at the same or lower cost. In the *Drawdown* and *Optimum* scenario the emissions reduction are calculated to be 11.5 and 25.3 gigatons of CO2e.

Wind power plays a large and essential role in any long-term projections towards a low-carbon future. As a renewable resource, wind does not require mining or drilling for fuel, and its costs are therefore not susceptible to fluctuations in fossil fuel prices. One of the concerns with wind electricity is intermittency: wind speeds vary on a seasonal and hourly basis, requiring back-up power or storage at certain times to meet electricity demand. The growth of offshore wind could be aided by renewable energy and portfolio standards that mandate a certain level of renewable use. Wind developers could also benefit from regulatory stability, such as feed-in-tariffs that guarantee a certain rate of return on wind energy, and tax incentives that encourage investment in low-carbon projects like wind by helping offset development costs. Public research and development, particularly for this immature technology, can also help decrease costs. Technology knowledge transfer could help spread wind power across borders.

# Literature Review

## State of Offshore Wind Energy technologies

Offshore wind energy systems include offshore wind farms built in ocean environments, usually in the body of waters located in the shallowest part of the continental margin (i.e. the continental shelf) which could be up to an average of 60 meters deep and 65 km wide before the continental slope (NGS, 2011). The ocean makes over 70% of the world’s surface area and it remains an abundant reserves of energy resource in the form of offshore wind, marine, and tidal energy.

Just like onshore wind energy, offshore wind energy involves capturing of energy from moving air. However, the underlying mechanism behind the ocean wind resource is much different. In offshore, there are events of land breeze, sea breeze, and prevailing wind depending on the distance of the wind farm from shore. Offshore wind farm situated within about 15km close to the shore (or nearshore wind farm) takes advantage of sunrise and sunset fluctuations between land and sea breeze respectively (triggered by differential heating of air over land and sea) to generate energy, while the far-offshore wind farm relies predominantly on the prevailing winds. The former has the benefit of producing cheaper electricity at the expense of visual impacts, while the later yields higher capacity factor at the expense of higher foundation and system integration costs, and the reduced economic life of turbines.

Offshore wind farm came into spotlight in 1991 when [Ørsted](https://www.google.com/search?q=%C3%98rsted&stick=H4sIAAAAAAAAAOPgE-LVT9c3NEzOycktyMgpUOLUz9U3MMkwM0vRkssot9JPzs_JSU0uyczP08_JT04EMYqt8svzUosA-kExdzwAAAA&sa=X&ved=2ahUKEwj48uf5wfDfAhXWUhUIHe7JCXQQmxMoATATegQIBxAH) deployed eleven units of 450 kW turbines (or 4.95 MW) about 4 meters deep and 2 km away from the shore of Vindeby, Denmark. The Vindeby wind farm (now decommissioned since 2017) lasted for 25 years and attained a capacity factor of about 22% with the turbines of 35 meters rotor and 35 meters hub height. In other regions, first offshore wind farm arrived United States waters in 2016 as 30 MW Block Island Wind Farm, China’s 102MW [Donghai Bridge Wind Farm](https://en.wikipedia.org/wiki/Donghai_Bridge_Wind_Farm) in 2010, UK’s 60MW North Hoyle Offshore Wind Farm in 2003, Germany’s 60 MW Alpha Ventus Offshore Wind Farm, Sweden’s 2.75 MW [Bockstigen](https://www.4coffshore.com/windfarms/bockstigen-sweden-se02.html) wind farm in 1998 which is now reputed as the World’s first offshore wind farm re-powering project in 2018. In October 2017, Scotland played host to the 30MW Hywind, the world’s first offshore wind farm using floating wind turbines located 25km from the shore at a water depth of 110 meters (REN21, 2018). In September 2018, a 659 MW Walney wind farm in the UK located 15 km from shore and varying water depths averaging 136 meters becomes the world’s largest offshore wind farm.

The idea of onshore wind power applications has been around for much longer, and this created a potentially opportunity for knowledge transfer from onshore wind innovation to offshore wind research and development. Though this did not significantly impacted the offshore wind technology learning rate as expected because of the difference in cost drivers.

Technology advancement has led to the sophistication of offshore wind turbines, control systems, foundation, and system integration to enable the exploitation of more abundant and steadier wind resource deeper offshore where higher capacity factors gives a good trade-off with the cost implications. There is no major technical disparity between wind turbine blades for onshore applications and the ones for offshore environment, except that offshore blades are usually of mega-watt scale (which means larger size) especially for current generations of offshore wind farms. This is largely due to higher wind resource, and lack of space constraints in offshore sites. Like onshore wind farms, offshore wind space is dominated by horizontal axis wind turbines which are usually heavier and thus lead to higher substructure costs compare to vertical axis wind turbines which have rotational axis perpendicular to the ground. Research and Development effort have been geared towards vertical axis wind turbines as the desire to go deeper offshore grows. Unlike the horizontal axis wind turbines (HAWT), the vertical axis (VAWT) counterparts are insensitive to wind direction and as such allows for larger rotor size to be deployed with increased rated power per turbine. Also, the operating and maintenance (O&M) cost is much lower for VAWT due to relative ease of handling, transportation, and accessibility of the drivetrain (Griffith, 2015).

Foundations represent an important component of costs (i.e. around 18% of total installed costs). Fixed foundations have mostly been used in utility-scale offshore wind farms (IRENA, 2016a). The majority of substructures currently used area monopiles (97%), and jackets (3%). Alternatively, floating technologies for deep offshore areas where having turbine foundations in the seabed is not suitable, are currently being tested as prototypes (*e.g.* Windfloat project in the coastline of Portugal) with several advantages such as: “static and dynamic stability provides sufficiently low pitch performance enabling use of commercial offshore wind turbines; second, its design and fabrication methodology allow for onshore assembly of the complete system including the turbine; third, its shallow draft allows for depth independent siting and wet tow (fully assembled and commissioned) to installation site” (Principal Power, 2015).

Offshore wind farms that have entered operation since 2010 are reaching capacity factors of 40% to 50%, after hovering around 20-35%, reflecting their increased siting further offshore where wind resources are higher. Projects currently under construction are expected to reach capacity factors of 40% to 55%. Over the years, offshore wind farms have moved further from shore and into deeper waters, increasing capital costs but also the capacity factor and electricity generation (Hahn and Gilman, 2014).

The global average installed costs for offshore wind infrastructures, between 2014 and 2018, for commissioned and proposed projects ranges from US$2,070/kW to US$5,077/kW , and approximately U US$2,583.5/kW in China (IRENA, 2015; REN21, 2016). The average installed cost for Europe is approximately US$4,309/kW based on 2014 dollar exchange rate.

The difference in costs among the regions are due in part to the varying installation and system integration requirements of wind farms further from shore, and the degree of complexity of the met-ocean (combined wind climate, ocean’s wave and salinity) conditions.

Although offshore wind remains significantly more expensive than onshore, the LCOE for offshore wind generation also declined by 18% between 2010 – 2017 (REN21, 2018). Due to the harsher marine environment, O&M costs for offshore wind are expected to be higher than onshore, in the average values ranging of US$0.07/kWh globally (IRENA, 2015). Additionally, floating wind onshore systems could be at the higher end of project costs where ground mounted wind offshore could provide near to medium term cost effectiveness. Floating offshore wind technology is expected to be more competitive in deep portion of the continental shelve where higher capacity factor is guaranteed.

## Adoption Path

### Current Adoption

The capacity of offshore wind farms grew significantly in the last years with an estimated 3.4 GW connected to grids, about double the additions in 2014, mostly in Europe (91%), for a world total exceeding 12GW (REN21, 2016). Germany accounted for about two-thirds of global new offshore (with a total of 2.2 GW), followed by the United Kingdom (571 MW), China (361 MW), the Netherlands (180 MW) and Japan (3MW), the only other countries to add capacity offshore in 2015.

The increase in capacity is also reflected in the generation of electricity from wind technologies, growing from 31 TWh in 2000 to around 25 TWh in 2014, 36 TWh in 2016, and 42 TWh in 2017. At a regional level in 2017, electricity generation from offshore wind farm was the highest in EU (*i.e.* 39 TWh); and China with 2.4 TWh. Offshore wind technologies generated in 2014, near 25 TWh of electricity, with 23.82 TWh in Europe.

Current adoption[[1]](#footnote-1) for offshore wind farms is estimated at 62 TWh which represents only 0.27% of total electricity generation, while wind onshore is about 4.4% of total electricity generation in 2018. Fossil fuels still represent the lion share of electricity generation (natural gas 22.8%, coal 38%, and oil 3.7%) (IEA WEO, 2018).

### Trends to Accelerate Adoption

As offshore wind technology moves from the demonstration stage towards wider commercialization, there is a need to deploy instruments to foster its global scale-up (IRENA, 2018a). The growth of offshore wind could be aided by renewable energy and portfolio standards that mandate a certain level of renewable use. Wind developers could also benefit from regulatory stability, such as feed-in-tariffs that guarantee a certain rate of return on wind energy, and tax incentives that encourage investment in low-carbon projects like wind by helping offset development costs. Public research and development, particularly for this immature technology, can also help decrease costs. Technology knowledge transfer could help spread wind power across borders.

Integration of offshore wind with other hydro-based energy or water management technologies could also improve adoption. For example, integration of offshore wind to hydropower systems could help mitigate curtailment issues by using surplus wind electricity in times of low demand to pump water up to the reservoir and released during times of high electricity demand and low wind. More so, offshore wind electricity could be coupled with desalination system for water purification, and hydrogen production systems. Sector coupling has demonstrated potentials for offshore wind adoption in China for example, where the first offshore wind power was actually deployed to power the 2010 Shanghai World Expo which placed emphasis on future cities development anchored on environmental sustainability, resource efficiency, and diversity. Similarly, Free Trade or Special Economic Zones around seaports could integrate adoption of offshore wind power.

As discussed earlier, multiple grid modeling studies have found that using renewable energy to meet 80-100% of electricity demand by 2050 is possible with today’s technologies. Yet Loftus *et al.* (2015) note that studies aiming for 100% renewable energy throughout the globe by 2050 call for annual wind deployment at rates roughly 33% to 300% faster than has been demonstrated historically for any single technology (Loftus *et al*., 2015). Projections aiming for full renewables by 2050 would therefore require much stronger policies and investment than many countries are currently pursuing or even planning—although such policies could put us on the path for a near-zero carbon system that many scientists say is necessary for global climate stability (Hansen *et al*., 2008).

### Barriers to Adoption

Increased adoption of wind offshore systems need for extended and improved grid connections, with increased transmission support and storage technologies to allow for increase integration of Variable Renewable Energy Sources (VRES) as wind and solar. This issue could be overcome by larger balancing areas and greater transmission capacity that could help avoid curtailment and increase the share of wind generation on the grid. Since offshore wind adds high capacity to the grid, the implication is that more reserve capacity will be needed to support the grid during low power contribution from offshore wind. The costs associated with this balancing requirement calls for electricity market reforms to ensure availability of reserve capacity from power plants which might have been retired by the deployment of offshore wind. With system integration costs and balancing costs factored-in, offshore wind costs could be much more expensive at system level than stated at the farm level.

High costs, challenging environmental conditions and regulatory and technical issues (REN21, 2016) are the most relevant barriers to offshore wind adoption. For wind offshore, although policy changes have delayed some development, the United Kingdom continued to lead in global total offshore wind capacity with over 6.8 GW at the end 2017 (achieving about 50% of its 14GW target for 2020) ; followed by Germany (5.4GW). China (2.8GW) overtook Denmark (1.3GW) after adding about 1.2GW capacity from 2016-2017. Netherland (1.1GW) comes next in the league of countries with gigawatt capacity installed. These regions play host to over 92% of the global installed offshore wind capacity (18.8GW) in 2017. Despite this global increase, deployment offshore has been relatively slow in parts of Asia, and North America. However, North America’s region of California has seen accelerated deployment of offshore wind, and offshore wind capacity growth outlook for the United States remain promising considering the US government support for the exploitation of outer continental shelve for wind power.

### Adoption Potential

Offshore wind technologies adoptions across the world remain promising as the concerns around visual impacts of onshore wind present a strong case for offshore wind adoption. While most of the climate scenarios in literature do not envisage large adoption from offshore wind power, it is intuitively expected that the large capacity advantage of offshore wind system will need to be leveraged in order to meet the projected wind energy share that is consistent with the Paris agreement target as onshore wind alone, though currently on track to the target, may not hit the target sooner enough.

Figure 1.1. and Figure 1.2 show the global capacity adoption and the corresponding global electricity generation projection respectively for both 2DS and B2DS scenarios. The results from International Energy Agency in the Energy Technology Perspectives (IEA, 2017) estimate global offshore wind power capacity continuing to grow steadily with or without strong climate policies from 18.8 GW in 2017 to 136 GW corresponding to 573 TWh electricity generation in 2050 in the lowest adoption scenario (*i.e. Reference Technology Scenario*), 410 GW corresponding to 1,693 TWh electricity generation in 2050 in the 2 Degrees Scenario (2DS); and 437 GW corresponding to 1,802 TWh electricity generation in 2050 in the highest mitigation scenario (*i.e.* Beyond 2 Degrees Scenario, B2DS). These scenarios represent 1.2%, 4%, and 4.1% respectively of global electricity generation by 2050. Figure 1.1 shows that the current capacity adoption need be increased by over 20 folds in the next 30 years to put offshore wind on the track to Paris.

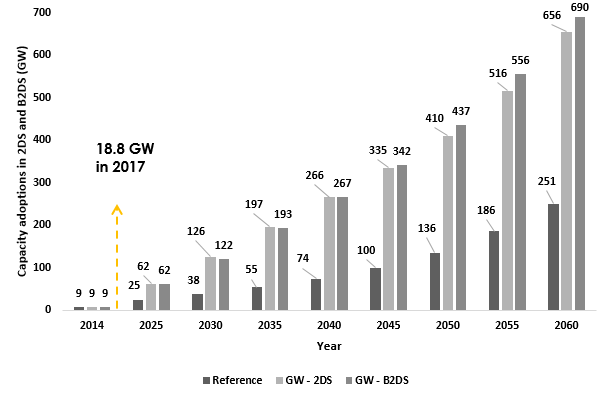


Figure 1.1 – Offshore wind capacity adoption projections in 2DS and B2DS scenarios (Adopted from IEA ETP, 2017)

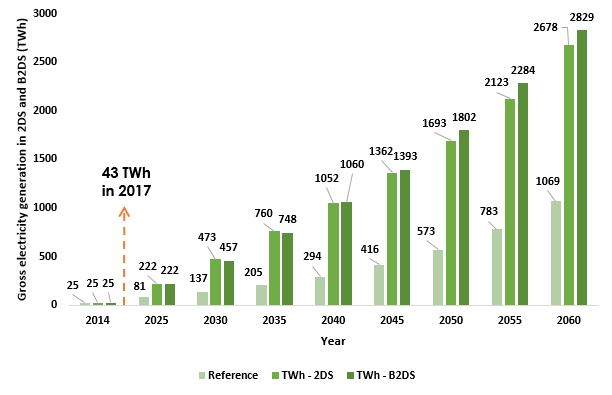


Figure 1.2 – Offshore wind electricity generation projections in 2DS and B2DS scenarios (Adopted from IEA ETP, 2017)

Results from the energy system models MESSAGE/MACRO and IMAGE/TIMER, under the EU AMPERE project (AMPERE, 2014) present very different expectations of wind capacity growth. In IMAGE/TIMER total wind capacity might reach 3,505 GW (in 450 scenario) and 3,676 GW (REFPol scenario).

In MESSAGE/MACRO, the expectations are lower in the REFPol scenario with 2,523 GW but higher in the 450 scenario with 3,894 GW (39% from offshore wind). Despite having similar socio economic assumptions that were harmonized in the AMPERE project, these differences are a result of the different characteristics of the models and technological detail available in each of them.

Greenpeace report from 2015 disclose the most ambitious scenario (i.e. Advanced Energy [R]evolution) of all the selected sources for wind cumulative capacity, explained by the main assumption behind it - 100% of electricity should be produced by RES in 2050. Figure 2.1 compare the long-term market projections for wind power of reports from 1999 to 2014 where we can see the range of projections for wind deployment dependent on the year of publication and scenarios assumptions.

|  |
| --- |
| Screen%20Shot%202016-10-28%20at%2016.54.17.pngScreen%20Shot%202016-10-28%20at%2016.54.51.png |

Figure 1.3 – Wind Power capacity long term market projections until 2030 (Adapted from Greenpeace, 2015)

The results presented show that a stronger adoption of wind turbines is possible if specific policies are put in place that put a price on carbon emissions, mitigation targets, as well as regulations that force fossil fuel companies to absorb some of their external costs on public health and the environment.

For IEA (2016b) and MESSAGE/MACRO model (AMPERE, 2014), the deployment of wind may rise 72% to 54% respectively when there is a limit on total carbon emissions. By defining a target 100% RES electricity generation, Greenpeace (2016) widens the scope for wind significantly, considering that it is possible a 561% compared to a Reference scenario in 2050.

Above, we presented several studies showing the role of wind technologies needed to put the world on the path under 2ºC degrees warming, the internationally-agreed threshold for avoiding potentially irreversible climate change; and estimating a range of possibilities for wind energy use and other less ambitious mitigation scenarios.

## Advantages and disadvantages of Wind Offshore

### Similar Solution

There are several solutions in the electricity generation sector that replace conventional electricity-generating technologies such as coal, oil, and natural gas power plants, and that could be considered similar solutions. Herein, it is considered similar solutions the ones that use the same resource: *i.e.* wind energy for electricity generation.

Besides wind offshore utility scale, there are alternative renewable energy technology with a difference on the level of agency (e.g. buildings level) and location (i.e. onshore).

* **Wind Onshore:** onshore utility-scale wind power technologies are located within the land boundary of a region, and widely spaced about 4 rotor diameters apart to minimize reduction of power output arising from downwind turbines operating in the wake of upwind turbines. Utility-scale onshore wind provides electricity at the same level of agency as the offshore wind power, relatively easier to build and maintain, but with potentially high visual issues which makes planning permissions and public acceptance more challenging.
* **Micro Wind Turbines:** electricity-generating wind turbines with capacity of 100 kilowatts or less. In lower-income countries, micro wind turbines can help expand access to electricity, giving people a way to light their homes or cook their evening meals, which can avoid emissions from dirty diesel generators or kerosene lamps. Micro turbines can also be placed on large structures, such as skyscrapers, to take advantage of stronger, steadier breezes.

### Arguments for Adoption

The ambitious targets against global climate change place emphasis on substituting the carbon-intensive electricity sector with cleaner technologies including offshore wind. Among other renewable energy systems, the higher power capacity and capacity factor per unit turbine makes offshore wind strategic in reaching high renewable power and energy penetration targets more quickly. In addition, offshore wind reduces the carbon intensity of electricity grid significantly by displacing net emissions from fossil-fired power plants. Offshore wind power is also favored in reducing the visual disamenity impacts associated with onshore wind power.

As a renewable resource wind does not require mining or drilling for fuel, and its costs are not susceptible to fluctuations in fossil fuel prices. The increased use of wind can help utilities hedge against the volatility of fossil fuels, and prepare for existing or future regulations pricing or limiting carbon emissions. The increased use of wind would also cut down on other air pollution emissions such as particulate matter, sulfur dioxide, and nitrous oxide, reducing related health problems and premature mortality. The increased use of wind would also decrease the use of water and the potential for water pollution from mining and drilling. According to the US DOE (2015), adoption of wind technologies compared to business as usual scenario results in savings on GHG emissions, air pollution, water use, and even electricity costs.

Given that wind offshore installations will in most cases be deployed to replace fossil fuel power plants, their carbon mitigation potential is significant. There are, of course, indirect emissions associated with these technologies manufacturing and installation, and this issue will be discussed in greater detail below, but according to the IEA, the large emission reductions resulting from substitution of fossil fuel-based electricity generation with wind electricity are orders of magnitude larger than emissions increases due to wind offshore lifecycle emissions and the variability that may come with a high penetration of wind electricity in future grids (IEA, 2014).

### Additional Benefits and Burdens

Offshore wind turbines and balance-of-system can be challenging to handle and/or transported by boats to offshore destinations. The degree of complexity also depends on the distance from shore and the depth of the continental shelve. Also, installations can be quite challenging where the ocean floor has complex topography and non-uniform. The enormity of wheeling the electricity generated in offshore wind facilities to the utility grid remains one of the major cost drivers. Unlike other renewable energy technologies such as solar PV, hydro, and geothermal power plants, offshore wind power is less constrained by location. Wind turbines are equipped with yaw mechanisms to yaw them towards good wind resource, and away from stormy wind. Also, the turbine blades are made sophisticated to provide pitching control. In addition, advancement in floating offshore wind technologies will facilitate exploitation of wind resource over large areas.

As seen before, though individual turbines at wind plants may need replacement after 20 to 30 years, the site does not need to be abandoned. New, more cost-effective turbines can be added, the infrastructure upgraded if necessary, and the plant returned to use - a process known as re-powering. Where turbines do require decommissioning, the salvage value often offsets the costs (Wiser and Yang, 2011).

According to REN21 (2016) offshore wind power face some challenges in the lack of transmission infrastructure, delays in grid connection, the need to reroute electricity through neighboring countries, lack of public acceptance, and curtailment where regulations and current management systems make it difficult to integrate large amounts of wind energy and other variable renewables.

Further, several studies using models of the electrical grid also have found that current renewable energy resources and technologies could reliably power 80-100% of the electrical grid, at the state, regional, and federal level (Arent *et al.*, 2014, Budischak *et al.*, 2013, Hart and Jacobson 2011[[2]](#footnote-2)). Wind along with solar often provides most of the energy demanded, supported by electricity supply from natural gas turbines and pumped hydro storage to match peaking demand.

Another concern with wind electricity generation, like solar, is intermittency. Offshore wind speeds vary on a seasonal and hourly basis depending on met-ocean conditions. This necessitates the need for back-up power or storage at certain times to meet electricity demand. An electric system increasingly powered by solar and wind will need modifications and investments to effectively accommodate the new energy sources. Improved forecasting techniques and combining wind and solar can reduce variability costs, although pumped hydro storage and peaking power plants may be needed to meet periods of increased energy demand. According to IRENA (2015), while this impact receives much attention in the literature and public debate, in large countries increased investment in transmission and distribution lines might be required if available renewable resources are located far from demand centers. Based on available data in UK context, Catapult (2016) estimates the resulting grid costs for transmission networks tend to average around US$0.02/kWh. Table 1.1. presents a comparison of selected pros and cons of the solution with others in the same sector and with the same energy source.

Table .1 Conventional versus wind technologies: some key impacts

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Conventional electricity Generation technologies | Wind Onshore | Wind Offshore | Micro Wind |
| *Land Area Requirement* | Medium | Low | Low | Low |
| *Water Requirement* | Very High | Low | Very Low | Negligible |
| *Visual Disamenity* | High | Very High | Very Low | Low |
| *GHG Emissions* | High | Very Low | Low | Negligible |
| *Electricity Generation Flexibility* | High | Low | Low | Low |
| *Handling Constraints* | Very High | High | Very High | Low |
| *Labor Requirement* | Very High | High | Very High | Low |
| *Grid Balancing Requirement* | Low | High | Very High | Nil |
| *Decommissioning Constraints* | Very High | High | Very High | Very Low |
| *Operation and Maintenance and Fuel Costs* | High | Low | Medium | Low |
| *System integration cost* | Medium | Medium | High | Low |
| *Foundation cost* | Medium | Medium | High | Low |

# Methodology

## Introduction

Project Drawdown’s models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for replacement of conventional electricity generation technologies (i.e. coal, oil, natural gas) and related emissions for an alternative solution (see the Drawdown RRS Model Framework and Guide for more details). These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model, but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units (TWh), and for investment costing, adoptions are also converted to implementation units (TW). The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2050 and the comparison of these scenarios (for the 2020-2050 segment) is what constitutes the results.

For this solution, the approach was to analyze the impacts of increased adoption of wind offshore systems. The models used for this analysis construct both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for wind offshore. Following project Drawdown methodological assumption (further description available on the Drawdown RRS Model Framework and Guide), in order to grasp the total impact of an increased adoption of the solution during the assessed time frame; the REF scenario assumes future adoption of wind offshore remains fixed at the current adoption (i.e. 2018) percentage of Total Addressable Market (TAM), estimated at 0.27 percent (62 terawatt-hours) of electricity generation. The TAM for the solution is based on the common project Drawdown projected global electricity generation in terawatt-hours till 2050 (Section 2.3.).

The developed alternative PDS scenarios, draw on existing adoption scenarios for wind in general which is split between onshore and offshore, or specifically wind offshore to model several alternative adoptions. The RRS model contains both financial and climate analyses in order to model the global and regional impacts of adoption in the PDS scenarios compared to the REF scenario. What the model thus prognosticates is the total financial costs and benefits of adoption cases for wind onshore/offshore, as well as the contribution of these adoptions can make to annual and cumulative emissions reduction.

## Data Sources

This section presents key data sources utilized in the mode to evaluate the adoption of wind offshore technologies. Data inputs for the model come from a variety of sources, primarily from peer-reviewed publications and from institutional reports. For all variable inputs, it was done a variable meta-analysis of existing literature to create low, high, and mean estimates. For each variable, it is conducted a sensitivity analysis of, on average, six data points reported in the literature and in some cases as many as 15. This allows to calculate robust and reliable inputs for the financial, technological and climate analyses that represent both optimistic and conservative estimates for the future costs and benefits of adopting this solution.

In literature, life cycle assessments (LCAs) have been conducted for offshore wind power technologies across the globe since the 1990’s the first commercial offshore wind power was commissioned.. LCAs determine the environmental impacts of products and technologies throughout their full lifetime, from raw material extraction and processing; to manufacturing and distribution; to use and maintenance; to disposal or recycling. LCAs include estimates of total greenhouse gas (GHG) emissions and other environmental impacts and resources used (*e.g.* water and land use, air pollutants emissions).

Published GHG indirect emission estimates for offshore wind power, have ranged from 8 to 35 g CO2eq/kWh over their lifetime (IPCC, 2014; Thomson & Harrison, 2015) . The wide span in results for wind reflects different assumptions around capacity factor, conversion efficiency, operating lifetime and quality of wind resource , as well as shore distance, and water depth. Lifetime of 20 – 25 years and capacity factor of 24 – 48% for offshore were have been used as inputs in estimation of GHG emissions result.

Modern wind turbines that meet International Electrochemical Commission standards are designed for a 20-year lifetime (Wiser and Yang, 2011). IRENA (2015) and Hertwich et *al.*, (2015) consider 25 years. LM Wind Power, the manufacturer of turbine blades that powered the first offshore wind farm in Vindeby, Denmark for 25 years pointed out that turbine blades for offshore applications need not be significantly different from their onshore counterparts as the blades do not come in contact with the ocean. However, it must be noted that the Vindeby wind farm was located nearshore, and the met-ocean conditions may not be significantly different from onshore. Therefore, it is expected that wind turbine blades for deeper offshore applications should meet higher strength and aerodynamic requirements to withstand loading.

Different approaches have been used trying to prognosticate wind energy costs; e.g. historical cost trends as a tool to forecast the future (*e.g.* Ferioli *et al.,* 2009) have been criticized (*e.g.* Rubin *et al.*, 2015) since they explicitly assume that future trends will replicate past ones. Learning curves start with the premise that increases in the cumulative production of a technology leads to a reduction in its costs through economies of scale. The learning rate is defined as the percent change in cost for every doubling in cumulative production or units installed. Nevertheless, renewable energy sources learning rates are projected to increase the competitive of the technologies, and ultimately cheaper than conventional sources, as is the case already in many regional markets. It is consensual that installation costs for offshore wind turbines will continue to decline, but it may not be so rapid for deeper offshore environment. Ederer (2015) presented a learning rate of 9.8% for Learning by Doing (LBD) considering shore distance and water depth. Other authors give learning rates in the range of 1 – 5% including consideration of one and two factors learning, capacity cost. Improvement in learning rate will play a significant role in achieving the targets for offshore wind, especially the deep offshore wind technologies.

A recent paper published in Nature Energy (Wiser *et al.,* 2016), presented results of an elicitation survey of 163 leading wind experts around the world referring that the LCOE of wind could fall 24-30% by 2030 and 35-41% by 2050 (median scenario) compared to 2014 levels. In the survey's median scenario, onshore wind is expected to remain less expensive than offshore, and fixed-bottom offshore is projected to be less expensive than floating wind turbines. Yet, experts anticipate bigger overall “*reductions (and more uncertainty) in the LCOE of offshore compared with onshore wind, and a narrowing gap between fixed-bottom and floating offshore costs, with especially big expected reduction in the LCOE of floating offshore wind between 2020 and 2030*”. According to this study, for fixed-bottom offshore wind, the “most highly rated advancements include increased turbine capacity ratings, design advancements for foundations and support structures, and reduced financing costs and project contingencies. Similar drivers rate highly for floating offshore wind, with an even greater emphasis on foundations and support structures, as well as installation processes” (Wiser *et al.,* 2016).

REN21 (2016) revealed that manufacturers and developers signed a declaration in order to drive the cost of offshore wind energy below 112$/MWh by 2020. IRENA (2016a) consider that total installed cost reduction potential for offshore wind could be 15% by 2025, emerging from lower installation costs. This will be a result of “*bigger turbines, increased efficiency of processes, increased on-land pre-assembly and commissioning of components, and more rapid foundation installation*” (IRENA, 2016a).

Due to the relatively recent deployment of offshore technologies, it is difficult to assess a learning rate based on past deployment. However, given its early stage of development, offshore wind technologies are likely to improve and go down in cost (Hahn and Gilman, 2014). Foundations and grid connection comprise a larger share of total investment cost, with foundations having substantial cost-reduction potential (IEA, 2013). Given this potential, the IEA assigns offshore wind a learning rate of 9% for its forecasts (2013), while the US DOE gives offshore wind a 10% learning rate for its low-cost wind scenario (DOE, 2015). Lemming *et al.* (2009) studied the potential for development of offshore wind power until 2050, assuming that the learning rate of 10% observed between 1985 and 2000 remains constant until 2030, after which it decreases to 5% (Lemming *et al*., 2009). Rubin *et al.* (2015) unfolds a 12% learning rate.

## Total Addressable Market

Solutions assessed in the Electricity Generation Sector share a common market for future adoption defined by the total terawatt-hours (TWh) of generation demanded from 2015-2060. This shared total addressable market (TAM) is used to bound this sector technologies rollout over time. The TAM is determined based on the assessment of estimations of current and future electricity generation from a combination of models and scenarios from different sources, including Greenpeace (2015); International Energy Agency (IEA) - Energy Technology Perspectives (IEA, 2017); IEA World Energy Outlook (WEO) (IEA, 2018); Equinor (2018); Ecofys (2018); The Institute of Energy Economics Japan (IEEJ) Outlook 2019 (2018) and Ram et al. (2019). See Project Drawdown report - Assessing the Total Addressable Market and Major Assumptions for more details on the methodology used to develop the electricity TAM. The updated 2019 study follows the same methodological approach with the inclusion of newer sources.

Four prognostications of the TAM for this assessment were derived by using comparable scenarios from each of the above-mentioned sources which were categorized by expected climate mitigation scenarios (i.e. Ambitious, Conservative, and Baseline) and the scale of deployment of renewable energy sources (RES) (i.e. 100% RES scenarios). The sources used mostly provide results at a decadal level, which were interpolated to provide annual values for Project Drawdown calculations.

The Ambitious Project Drawdown TAM Scenario is constructed from the average of yearly values of four scenarios: the IEA (2017) 2D Scenario, the IEA (2017) B2D scenario, Renewal Scenario from Equinor (2018), and IEA (2018) WEO SD scenario. The Conservative Project Drawdown TAM Scenario follows the average yearly values of the IEA (2018) WEO New Policy scenario (NPS); Reform Scenario from Equinor. (2018), IEEJ Outlook (2018) Advanced Tech scenario, and IRENA (2019b) Roadmap 2050 REmap case. The Baseline Project Drawdown TAM Scenario is built by the average of the Equinor (2018) Rivalry Scenario, IEEJ Outlook (2018) Reference Scenario, IEA (2017) Reference Case and IEA (2018) WEO Current polices Scenario (CPS). These three Project Drawdown TAM scenarios show an estimated range of electricity generation from 45,286TWh to 49,706TWh by 2050. Baseline TAM is used for PD Plausible scenario assessment.

An ambitious TAM scenario for a 100% RES by 2050, which is aligned to project Drawdown Optimum and Drawdown scenarios, utilizes the Greenpeace (2015) Advanced [R]evolution Scenario, Ram et al (2019) analysis and Ecofys (2018) 1.5ºC degree scenario were considered. The estimated electricity generation for this TAM reaches 70,942 TWh by 2050.

## Adoption Scenarios

As other electricity generation technologies that have rapidly increased the adoption in recent years, wind offshore has increased significantly from 3,056 MW in 2010 to 18,726 MW in 2017 the total installed capacity (IRENA, 2019a). This recent growth, coupled with still not being a mature technology, brings additional uncertainties to project global wind offshore adoption over the next 30 years.

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

### Reference Case / Current Adoption

For the Reference (REF), adoption is fixed at the current adoption[[3]](#footnote-3) (in percent) of the market. Historical data of offshore wind generation until 2017 was retrieved from IRENA (2019a) and 2018 was estimated by PD representing 0.27% of total generation. That is, the current share of total electricity generation (TWh) provided by wind offshore is constant throughout the study period to 2050. As the market grows, the total number of wind plants adopted grows equally to maintain the percent adoption at its starting value in 2014. It is acknowledged that this, in reality, may not be a “business as usual” considering changes taking place worldwide, but it allows measurement of the impact of recent and even more aggressive policies on greenhouse gas emissions.

### Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for the solution (i.e. wind offshore), to compare the impact of an increased adoption of the solution to a reference case scenario, being:

#### Plausible Scenario

This scenario represents an incremental and plausible growth of renewable energy solutions using medium to high growth trajectories to 2050 depending on the current maturity levels of the technology, and bounded by existing ambitious projections from other global energy systems models. For offshore wind turbines, this scenario is based on the evaluation of yearly averages of four optimistic scenarios from: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Equinor (2018) Renewal Scenario; using a medium growth trajectory.

#### Drawdown Scenario

This scenario is optimized to reach drawdown by 2050 using more ambitious projections from existing sources. The scenario projects a 100% adoption of non-fossil fuel-based technologies in 2050; mainly RES but also includes several technologies that are considered transitional solutions (as nuclear energy) (See section 6). For offshore wind turbines, this scenario is based on the evaluation of yearly averages of four optimistic scenarios from: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Equinor (2018) Renewal Scenario; using a high growth trajectory.

#### Optimum Scenario

This scenario represents the most optimistic case, in which clean, renewable energy solutions such as wind, solar, and other renewable energy sources capture 100% of electricity generation by 2050, with both fossil fuels and transitional solutions fully phasing out by 2050. In this scenario, wind offshore adoption is based on the yearly average values of three 100% RES scenarios of electricity generation by 2050, being Greenpeace (2015) Advanced Energy [R]evolution Scenario; Ram et al. (2019) scenario and Ecofys (2018) 1.5ºC scenario.

## Inputs

### Climate Inputs

In order to calculate the climate impacts of the project Drawdown scenarios, in terms of maximum annual emissions reduction, total emissions reduction, and PPM equivalent, it was estimated wind offshore electricity generation globally and regionally from 2020-2050 and then calculated the emissions reductions due to the replacement of conventional electricity generation sources with the solution. The detailed methodology of these calculations is available at the Project Drawdown Integration Methodology report.

While being a renewable energy technology, wind onshore technologies do not have direct emissions related to combustion of fuels. Project Drawdown modeling considers the analysis of indirect emissions related to the different factors that contribute to a LCA for wind turbines. In modeling the lifecycle emissions of wind offshore adoption in the scenarios, it is used a fixed value (t CO2-eq per TWh) considering information from several studies, rather than a decreasing one due to the difficulty of projecting future grid-tied emissions on a regional basis. Our climate results will thus be more conservative than would be the case if we assumed a decreasing average lifecycle emissions value for wind offshore (Table 2.1).

Table . Climate Inputs

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Indirect CO2 Emissions (Solution) | *t CO2-eq/TWh* | 6,114 - 22,389 | 14,252 | 23 | 7 |

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[[4]](#footnote-4).

### Financial Inputs

RRS model constructs PDS adoption scenarios for utility-scale PV generation globally and regionally for each year until 2050. It is modelled both the capital costs and the fixed and variable OM costs associated with the alternative scenarios compared to those of the REF scenario. Detailed description of the methodology used is available in the Drawdown RRS Model Framework and Guide.

The financial calculations examine the first cost in US$ per kW and the operating cost in US$ per kW (fixed costs) and US$ per kWh (variable costs). For this, many inputs estimating annual output and lifetime output per wind offshore electricity generation, along with first costs (per functional unit), were calculated.

For the solution (wind offshore), the conventional current mix of fossil fuel electricity generation technologies (coal, gas and oil) replaced were identified. Costs and operation for both generation technologies (solution and conventional) were considered to obtain the differential result.

As already described in the literature review section, the variability of investment costs is still significant amongst world regions. The financial inputs used in the model consider an average installation cost of US$3,486 per kilowatt, with a learning rate of 8.2% resulting in first costs of US$2,428 per kilowatt in 2030 and US$2,025 per kilowatt in 2050. An average capacity factor of 39 percent is used for offshore wind turbines, compared to 57 percent for conventional technologies such as coal, natural gas, and oil power plants. Variable operation and maintenance costs of US$0.017 per kilowatt-hour are considered for offshore wind, compared to US$0.005 per kilowatt-hour for the conventional technologies. The input values for fixed costs are US$84.80 per kilowatt for offshore wind and US$34.65 for conventional electricity generation technologies..

Fuel prices for conventional technologies are derived from IEA (2019) data, averaging 2007-2018 historical registries for oil, coal and natural gas used for electricity generation and calculated through a weighted average by fuel from the current electricity generation mix.

Additionally a discount rate is fixed at 9.68 percent appropriate for utility-scale projects and used across all Drawdown electricity generation solutions with this level of agency (Tables 2.2. and 2.3). The discount rate used herein was benchmarked to the Power generation technologies of the PRIMES model used in the impact assessment of the EU 2030 targets, that considers 9% (EC, 2014).

Table . Financial Inputs for Conventional Technologies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| First costs (Conventional) | *US$2014/kW* | 470.5 – 3,101 | 1,786 | 24 | 8 |
| Fixed Operation and Maintenance Costs (Conventional) | *US$2014/kW* | 3.44 – 65.86 | 32.95 | 18 | 4 |
| Variable Operation and Maintenance Costs (Conventional) | *US$2014/kWh* | 0.0014 – 0.0079 | 0.0048 | 22 | 7 |
| Fuel Price (Conventional) | *US$2014/kWh* |  | 0.0492 |  | 1 |
| Learning Rate Factor (Conventional) | % |  | 2.00% |  |  |

Table .3 Financial Inputs for Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| First costs (Solution) | *US$2014/kW* | 2,327-4,645 | 3,486 | 52 | 12 |
| Fixed Operation and Maintenance Costs (Solution) | *US$2014/kW* | 59.16 – 140.80 | 99.98 | 11 | 6 |
| Variable Operation and Maintenance Costs (Solution) | *US$2014/kWh* | 0 – 0.047 | 0.017 | 7 | 4 |
| Learning Rate Factor (Solution) | % | 2.6 – 13.9 | 8.20% | 8 | 4 |

### Technical Inputs

Table 2.4 present the technical inputs used for the conventional technologies in the RRS model. A lifetime capacity of 68,815 hours (around 23 years) was calculated for wind offshore, depending on the average powerplant annual use. A capacity factor of 34% is used reflecting the global average from the data collected (Table 2.5).

Table .4 Technical Inputs Conventional Technologies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Lifetime Capacity (Conventional) | *hours* | 121,807 – 222,351 | 172,079 | 12 | 6 |
| Average Annual Use (Conventional) | *hours* | 3,337– 6,587 | 4,962 | 23 | 4 |

Table .5 Technical Inputs Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Lifetime Capacity (Solution) | *hours* | 68,631 – 91,508 | 80,070 | 9 | 8 |
| Average Annual Use (Solution) | *hours* | 2,549 – 4,315 | 3,432 | 26 | 7 |

## Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology are available on the Project Drawdown Reduction and Replacement Solutions (RRS) Model Framework and Guide report. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

1. The results from the different sources are depicted at a 5 year or 10 years’ basis and it were needed yearly, therefore data interpolation was made using the best fit trends (*i.e.* generally 3rd polynomial but 2nd polynomial or S curve were also used).
2. Of the sixteen (16) scenarios recorded, twelve (12) are not split between onshore and offshore. The splitting is done based on global onshore/offshore wind electricity generation share presented by the IEA Energy Technology Perspective (2017) for the trio of Reference Technology, 2DS, and B2DS scenarios. The IEA ETP (2017) wind onshore split ratios for Ref- Tech, 2DS, and B2DS are used for splitting adoption data under the baseline, conservative, ambitious/100% RE cases respectively. Among the 16 scenarios for offshore wind adoption, only the 3 scenarios from IEA ETP (2017), and the one scenario from Ram et al. (2017) have split offshore wind from the sources. All other 12 scenarios from 6 sources were manually split using yearly- and scenario-based ratios derived from the established offshore wind share in the IEA ETP (2017) source.

## Integration

The complete Project Drawdown integration documentation with details on how all solution models in each sector are integrated, and how sectors are integrated to form a complete system will be available at [www.drawdown.org](http://www.drawdown.org). Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

Therefore, the data derived from individual solutions models was then inputted into sector-level integration models to generate final results for all solutions within a global system. The links between this sector and all the others is important, but major interactions occur with energy demand-side sectors like Transport and Buildings and Cities.

Through the process of integrating wind onshore and offshore farms with other solutions, the total addressable market for electricity generation technologies was adjusted to account for reduced demand resulting from the growth of more energy-efficient technologies (for example: LED lighting and heat pumps) as well as increased electrification from other solutions like electric vehicles and high-speed rail. Grid emissions factors were calculated based on the annual mix of different electricity generating technologies over time. Emissions factors for each technology were determined through a meta-analysis of multiple sources, accounting for direct and indirect emissions.

## Limitations / Further Developments

The readiness of a country’s power system for integration of offshore wind power depend on dynamic factors which include availability of sufficient spinning reserves, cost of competing conventional power plants, transmission capacity, distance to sub-station and/or load centers, reformed electricity market, enabling regulatory and support policies. To avoid complications, not all of these factors which change from time to time could be accounted for in the Drawdown modeling approach. Some of the factors are assumed constant, or consistent with the target outcomes of the model. The Drawdown model incorporates parameters that account for or estimate financial, environmental, and technical metrics which are mostly endogenous to offshore wind performance variables including capacity factor, economic life, learning rate, and costs.

In the Drawdown modeling approach, effects of variables such as shore distance and water depth are assumed exogenous to cost variables for offshore wind power, and therefore not directly accounted for. In addition, the effects of regulatory and policy environments including Renewables Portfolio Standards, Production Tax Credits, penalty factor for entities not meeting contract obligations are assumed constant.

# Results

In the following section are depicted selected results derived from the RRS model evaluating the impact of increased adoption of Wind Offshore Farms for electricity generation when compared to conventional technologies.

## Adoption

Comparing the results from the three modeled scenarios to the Reference Scenario allow to estimate the climate and financial impacts of increased adoption of wind systems. The Plausible Scenario (PDS1) projects 4.2 percent of total electricity generation worldwide coming from offshore wind by 2050. Offshore wind grows slowly but steadily, reaching 1,918 TWh by 2050 (Figure 3.1). In the Drawdown Scenario (PDS2) the market share reaches 3.2 percent, while Optimum Scenario (PDS3) 5.8 percent of those scenarios TAMs. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percent.

The PD scenarios project an important growth in offshore wind, dominated by China, the EU, and the US. Projections consider that much of the growth in offshore wind will take place in China, where costs will likely be lower. Figure 3.1 depicts the long term pathway trajectories for the different scenarios of offshore wind farms adoption.

Table . World Adoption of the Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| **Plausible** | **Drawdown** | **Optimum** |
| Wind Offshore | *Electricity Generation (TWh)* | 24.89 | 1,918 | 2,256 | 4,108 |
| *(% market)* | 0.11% | 4.2% | 3.2% | 5.8% |

Figure 3.1 World Annual Adoption 2015-2060

## Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction and atmospheric concentration changes. For a detailed explanation of each result, please see the glossary (Section 6).

With its low GHG emissions at LCA level, the adoption for offshore wind electricity portrayed in the PD scenarios could reduce global GHG emissions at a significant amount. The Plausible Scenario results in the avoidance of 11.49 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. Both the Drawdown and Optimum Scenarios are more ambitious in the growth of offshore wind technologies, with impacts on greenhouse gas emissions reductions over 2020-2050 of 13.28 and 28.38 gigatons of carbon dioxide-equivalent respectively. These reduced emissions would help to avoid costs related to climate change damages, improved public health, air quality and water consumption. Tables 3.2 and 3.3. provide additional information on the climate impacts of the solution adoption.

Table . Climate Impacts

|  |  |  |
| --- | --- | --- |
| **Scenario** | **Maximum Annual Emissions Reduction** | **Emissions Reduction in 2050** |
| *(Gt CO2-eq/yr.)* | *(Gt CO2-eq/year)* |
| ***Plausible*** | 0.88 | 0.88 |
| ***Drawdown*** | 1.05 | 1.05 |
| ***Optimum*** | 1.96 | 1.96 |

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined). After integration, the impact on emission reduction for this solution is 10.8 gigatons of carbon dioxide-equivalent in the *Plausible* scenario, 10.5 gigatons of carbon dioxide-equivalent for the *Drawdown* Scenario and 25.3 gigatons of carbon dioxide-equivalent for the *Optimum* Scenario. Figure 3.2. show the world annual emissions reduction trajectories for the different scenarios for the long term.

Table . Impacts on Atmospheric Concentrations of CO2-eq

|  |  |  |
| --- | --- | --- |
| **Scenario** | **GHG Concentration Change in 2050** | **GHG Concentration Rate of Change in 2050** |
| *PPM CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| **Plausible** | 0.99 | 0.07 |
| **Drawdown** | 1.14 | 0.09 |
| **Optimum** | 2.44 | 0.16 |

Figure . World AnnualGreenhouse Gas Emissions Reduction (2015-2060)

## Financial Impacts

The RRS model results for the PDS1 (*Plausible* Scenario) show that the net cost compared to the *Reference* Scenario would be US$632 billion from 2020-2050, and around US$423 billion in savings over the same period. Increasing the use of offshore wind from about 0.27 percent in 2018 to 3.8 percent of world electricity generation by 2050 would require an estimated US$1,406 billon in cumulative first costs.

As abovementioned, both the *Drawdown* and *Optimum* Scenarios are more ambitious in the growth of offshore wind technologies, with increased positive impacts on greenhouse gas emission reductions and costs over 2020-2050 as described in Table 3.4.

Table . Financial Impacts

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Operating Cost Savings** | **Lifetime Cashflow Savings NPV (of All Implementation Units)** |
| *2015-2050 Billion USD* | *2015-2050 Billion USD* | *2020-2050 Billion USD* | *Billion USD* |
| **Plausible** | 1,429 | 654 | 324 | -56.1 |
| **Drawdown** | 1,639 | 745 | 375 | -61.7 |
| **Optimum** | 2,960 | 1,402 | 799 | -126.1 |

# Discussion

Offshore wind power presents high capacity, high capacity factor, complementarity (with solar PV), independence of volatile fuel prices, and reduced visual disamenity advantages in meeting the targeted energy pathway consistent with the ambitious Paris Agreement.

Project Drawdown models three scenarios where wind offshore power provides 3 to near 6% of world electricity generation by 2050. As abovementioned these scenarios could significantly reduce future GHG emissions and help drawdown the amount of carbon in the atmosphere.

One of the most important determinants of future wind technologies use will be cost. After a brief increase in mid 2000 due to lack of competition in offshore wind market, the LCOE of offshore wind has again been on the slow decline, and could be potentially competitive with new fossil fuel plants in several countries in the foreseeable future. It is also expected a sharp declining of first costs as the size of the turbines and number of projects increase. Financial and regulatory stability could help ensure that offshore wind power technologies continue to come down in price, such as long-term tax credits and incentives for production and installation. The use of wind is also aided by renewable energy and portfolio standards; a price or limit on carbon emissions; and policies or regulations that internalize the external costs of fossil-fired power plants.

Notwithstanding its local impacts, using offshore wind power to reduce the use of fossil power generation brings net improvement in public health and environmental benefits, especially related to reduced air pollution since offshore wind power produces no direct air emissions and has very low lifecycle emissions (DOE, 2015).

As projected by the several sources, offshore wind could potentially play a large role in future global energy use. This study suggests offshore wind could result in net savings even at currently projected installation costs of US$3,486/kW. However, the roll out of offshore wind could be further boosted by improvements in the technology and reductions in costs. Such technology improvements and costs reductions would be aided by increased R&D into offshore wind technologies for deep offshore applications.

## Limitations

The accelerated deployment of new offshore wind capacity will not be without the daunting engineering and economic challenges, however, as currently most electricity markets and grids are in many cases not suited for a high penetration of intermittent RES use. Wind speeds vary on a seasonal and hourly basis, requiring back-up power or storage at certain times to meet electricity demand. The increased penetration of offshore wind and solar power will require investments and improvements in grid infrastructure and the flexibility of power systems to avoid the adverse effects of variable renewable energy on the grid. Yet studies and real-world experience suggest these costs are manageable and affordable, costing less than fossil fuels when externalities are taken into account. Further, many regions do not yet have a centralized electric system designed around fossil use, and may more easily create a more flexible or distributed system.

There will be economic, policy, and social hurdles to overcome on the pathway set out in these scenarios, and some of these will require significant changes to the way electricity is bought, sold and used. But given the immense climate and financial impacts of global wind farms adoption, it is imperative that these challenges are taken in order to realize the benefits.

## Benchmarks

Table 4.1 depicts a benchmark of Project Drawdown results for 2050 on the three developed scenarios to other six publicly available scenarios from IEA (2017) and Greenpeace (2015). The results of the PD *Plausible* Scenario is aligned with B2DS and 2DS Scenario of IEA ETP (2017), which estimates the growth of offshore wind to reach around 4 percent of the market in 2050. Compared to the Greenpeace Energy [R]evolution Scenario, however, PD results on Plausible scenario for adoption are nearly half, with electricity generated from offshore wind turbines representing up to 8 percent of the market in 2050 (Greenpeace, 2015).

Table . Benchmarks

|  |  |  |
| --- | --- | --- |
| **Source and Scenario** | **Electricity Generation in 2050 (TWh)** | **Market Share in 2050 (%)** |
| **Project Drawdown – Plausible Scenario (PDS1)** | **1,918** | **4,2%** |
| **Project Drawdown – Drawdown Scenario (PDS2)** | **2,256** | **3.2%** |
| **Project Drawdown – Optimum Scenario (PDS3)** | **4,108** | **5.8%** |
| Greenpeace Energy [R]evolution (2015) – Reference Scenario | 521 | 1.0% |
| Greenpeace Energy [R]evolution (2015) – Energy Revolution Scenario | 4,008 | 8.0% |
| Greenpeace Energy [R]evolution (2015) – Advanced Energy Revolution Scenario | 6,330 | 9.4% |
| IEA Energy Technologies Perspectives (2017) – Reference Technology Scenario | 573 | 1.2% |
| IEA Energy Technologies Perspectives (2017) – 2DS | 1,693 | 4.0% |
| IEA Energy Technologies Perspectives (2017) – B2DS | 1,802 | 4.1% |

# References

American Wind Energy Association. (2015). *Wind Energy Helps Build a More Reliable and Balanced Electricity Portfolio.* Retrieved from: http://awea.files.cms-plus.com/AWEA%20Reliability%20White%20Paper%20-%202-12-15.pdf.

AMPERE. (2014). *AMPERE Database, Regions Definitions,* EU FP7 AMPERE Project. Retrieved from: https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB/dsd?Action=htmlpage&page=about#regiondefs

Arent, D., Pless, J., Mai, T., Wiser, R., Hand, M., Baldwin, S., Heath, G., Macknick, J., Bazilian, M., Schlosser, A. (2014). Implications of High Renewable Electricity Penetration in the US for Water Use, Greenhouse Gas Emissions, Land-Use, and Materials Supply. *Applied Energy, 123, 368–77.*

Black & Veatch for NREL. (2012). *Cost and performance data for power generation technologies. Black & Veatch, National Renewable Energy Laboratory.* Retrieved from https://www.bv.com/docs/reports-studies/nrel-cost-report.pdf

BNEF. (2014). *Sustainable Energy in America 2014 Factbook.* New York, NY: Bloomberg New Energy Finance. Retrieved from: http://about.bnef.com/white-papers/sustainable-energy-in-america-2014-factbook/

BP. (2014). *Statistical Review of World Energy 2014.* Retrieved from: http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html

Brown, C., Poudineh, R., & Foley, B. (2015). *Achieving a cost-competitive offshore wind power industry: what is the most effective policy framework?* Oxford Institute for Energy Studies. https://doi.org/10.26889/9781784670375

Budischak, CC., Sewell, D., Thomson, H., Mach, L., Veron, D.E., Kempton, W. (2013). Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. *Journal of Power Sources, 225, 60–74.*

Carbon Trust. (2008). *Offshore wind power: big challenge, big opportunity - Carbon Trust.* The Carbon Trust. Retrieved from https://www.carbontrust.com/resources/reports/technology/offshore-wind-power/

Citi Global Perspectives and Solutions. (2015). E*nergy Darwinism II. Why a Low Carbon Future Doesn’t Have to Cost the Earth.* Retrieved from: https://www.privatebank.citibank.com/home/fresh-insight/gps-energy-darwinism.html

Dalla Longa, F., Kober, T., Badger, J., Volker, P., Hoyer-Klick, C., Hidalgo Gonzalez, I., … Joint Research Centre. (2018). *Wind potentials for EU and neighbouring countries input datasets for the JRC-EU-TIMES model.* Joint Research Center, Europe.

Danish Energy Agency and Energynet. (2012). *Technology Data for Energy Plants Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion.* Danish Energy Agency and Energinet.dk. Retrieved from: https://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Forskning/Technology\_data\_for\_energy\_plants.pdf

DNV GL. (2018). *DNV GL Energy Transition Outlook 2018: A global and regional forecast of the energy transition to 2050.* DNV GL. Retrieved from https://eto.dnvgl.com/2018/

DOE (n.d.). *Wind Manufacturing and Supply Chain.* U.S. Department of Energy. Retrieved January 3, 2019, from https://www.energy.gov/eere/wind/wind-manufacturing-and-supply-chain

DOE. (2015). *Wind Vision: A New Era for Wind Power in the United States.* Washington DC: U.S. Department of Energy. Retrieved from: http://energy.gov/sites/prod/files/WindVision\_Report\_final.pdf.

DOE. (2016). *2015 Wind Technologies Market Report | Department of Energy.* US Department of Energy, Office of Energy Efficiency and Renewable Energy. Retrieved from https://www.energy.gov/eere/wind/downloads/2015-wind-technologies-market-report

Dolan, S. L., Heath, G.A. (2012). Life Cycle Greenhouse Gas Emissions of Utility‐Scale Wind Power. *Journal of Industrial Ecology 16, no. s1, S136–54.*

E.ON Climate & Renewables. (2012). *Rampion Offshore Wind Farm-Carbon Balance.* RSK Environmental Ltd. Retrieved from https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010032/EN010032-001550-6.1.30%20Carbon%20Lifecycle%20and%20Balance.pdf

Ecofys. (2018). *Energy transition within 1.5°C: A disruptive approach to 100% decarbonisation of the global energy system by 2050.* Ecofys - A Navigant Company. Retrieved from: https://www.ecofys.com/files/files/ecofys-a-navigant-company-2018-energy-transition-within-1.5c.pdf

Ederer, N. (2015). Evaluating capital and operating cost efficiency of offshore wind farms: A DEA approach. *Renewable and Sustainable Energy Reviews, 42, 1034–1046.* https://doi.org/10.1016/j.rser.2014.10.071

EIA. (2013). *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants.* U.S. Energy Information Administration (EIA) under the U.S. Department of Energy. Retrieved from https://www.eia.gov/outlooks/capitalcost/

Equinor. (2018). *Equinor’s Energy Perspectives 2018: A Call for Action.* Equinor. Retrieved from https://www.equinor.com/en/how-and-why/sustainability/energy-perspectives.html

European Commission. (2014). *Impact Assessment accompanying the Communication from the European Commission: A policy framework for climate and energy in the period from 2020 to 2030.* European Commission.

European Wind Energy Association. (2013). *Deep water. The next step for offshore wind energy.* Retrieved from: http://www.ewea.org/fileadmin/files/library/publications/reports/Deep\_Water.pdf

Ferioli, F, Schoots, K., van der Zwaan, B.C.C. (2009). Use and limitations of learning curves for energy technology policy: a component-learning hypothesis. *Energy Policy 37, 2525-2535.*

Garcia Gusano, D., Iribarren, D., Martín-Gamboa, M., Dufour, J., Espegren, K., Lind, A. (2016). Integration of life-cycle indicators into energy optimisation models: the case study of power generation in Norway. *Journal of Cleaner Production 112, 2693-2696.*

Greenacre, P., Gross, R., Heptonstall, P., & UKERC. (2010). *Great expectations: the cost of offshore wind in UK waters - understanding the past and projecting the future*. London: UK Energy Research Centre.

Greenpeace. (2014). *Global Wind Energy Outlook 2014.* Retrieved from: http://www.gwec.net/wp-content/uploads/2014/10/GWEO2014\_WEB.pdf

Greenpeace. (2015). *World Energy [R]evolution, a sustainable world energy outlook*. Retrieved from: http://www.greenpeace.org/international/Global/international/publications/climate/2015/Energy-Revolution-2015-Full.pdf

Griffith, D.T (2015) *Innovative Offshore Vertical-Axis Wind Turbine Rotors. In Sandia Energy.* Sandia National Laboratories. Retrieved from: https://energy.sandia.gov/energy/renewable-energy/wind-power/offshore-wind/innovative-offshore-vertical-axis-wind-turbine-rotors/

GWEC. (2017). *Wind Numbers | GWEC.* Retrieved November 14, 2018, from http://gwec.net/global-figures/wind-in-numbers/

Hahn, M., Gilman, P. (2014). *Offshore Wind Market and Economic Analysis: 2014 Annual Market Assessment.* Burlington, MA: Navigant Consulting. Retrieved from: http://energy.gov/sites/prod/files/2014/08/f18/2014%20Navigant%20Offshore%20Wind%20Market%20&%20Economic%20Analysis.pdf.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D.L., Zachos, J.C. (2008). Target atmospheric CO2: where should humanity aim? *Open Atmospheric Science Journal 2, 217–31.*

Hart, E.K., Jacobson, M.Z. (2011). A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables. *Renewable Energy 36, no. 8, 2278–86.*

Hayashi, D., Huenteler, J., & Lewis, J. I. (2018). Gone with the wind: A learning curve analysis of China’s wind power industry. *Energy Policy, 120, 38–51.* https://doi.org/10.1016/j.enpol.2018.05.012

Hayward, J. A., Graham, P. W. (2017). *Electricity generation technology cost projections: 2017-2050.* Commonwealth Scientific and Industrial Research Organisation (CSIRO). Retrieved from https://publications.csiro.au/rpr/pub?pid=csiro:EP178771

Hayward, J., Graham, P.W. (2013). A global and local endogenous experience curve model for projecting future uptake and cost of electricity generation technologies. *Energy Economics, 40, 537-548.* https://doi.org/10.1016/j.eneco.2013.08.010

Hertwich, E., Gibon, T., Bouman, E., Arvesen, A., Suh, S., Heath, G., Bergesen, J., Ramirez, A., Vega, M., Shi, L. (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences of the United States of America (PNAS) vol. 112, nº20, 6277-6282*. Retrieved from: www.pnas.org/cgi/doi/10.1073/pnas.1312753111

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case*. Energy 30, 2042–2056.* Retrieved from http://www.univie.ac.at/photovoltaik/umwelt/LCA\_japanstudy.pdf

IEA (2017). *Energy Technology Perspectives 2017 - Catalysing Energy Technology Transformations.* International Energy Agency (IEA). Paris, France. Retrieved from: <https://www.iea.org/etp/>

IEA (2017). *Energy Technology Perspectives 2017* (p. 443). International Energy Agency. France. Retrieved from: https://www.iea.org/etp/etp2017/

IEA (2018). *World Energy Outlook 2018.* International Energy Agency (IEA). Paris, France. Retrieved from : <https://webstore.iea.org/world-energy-outlook-2018>

IEA and NEA (2010). *Projected Costs of Generating Electricity – edition 2010*. Organisation for Economic Co-operation and Development - International Energy Agency and Nuclear Energy Agency. France. Retrieved from http://www.worldenergyoutlook.org/media/weowebsite/energymodel/ProjectedCostsofGeneratingElectricity2010.pdf

IEA and NEA (2015). *Projected Costs of Generating Electricity – edition 201*5. Organisation for Economic Co-operation and Development - International Energy Agency and Nuclear Energy Agency. France. Retrieved from https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf

IEA. (2010). *Energy Technology System Analysis Programme (ETSAP) - Technology Brief E02.* International Energy Agency (IEA). Retrieved from https://iea-etsap.org/index.php/energy-technology-data/energy-supply-technologies-data

IEA. (2013). *Technology Roadmap: Wind Energy*. Paris, France. Retrieved from: https://www.iea.org/publications/freepublications/publication/Wind\_2013\_Roadmap.pdf.

IEA. (2014). *Energy Technology Perspectives 2014 - Harnessing Electricity’s Potential.* Retrieved from: http://www.iea.org/etp/etp2014/.

IEA. (2016a). *Next Generation Wind and Solar Power – From cost to value.* International Energy Agency and Clean Energy Ministrial. OECD/IEA, Paris. Retrieved from: https://www.iea.org/publications/freepublications/publication/NextGenerationWindandSolarPower.pdf

IEA. (2016b). *Energy Technology Perspectives 2016 - Towards Sustainable Urban Energy Systems.* International Energy Agency. OECD/IEA, Paris. Retrieved from: https://www.iea.org/publications/freepublications/publication/EnergyTechnologyPerspectives2016\_ExecutiveSummary\_EnglishVersion.pdf

IEA (2019). Energy Prices and Taxes – Quarterly Statistics – First Quarter 2019. International Energy Agency. OECD/IEA, Paris.

IEEJ. (2018). *IEEJ Outlook 2019 — Energy transition and a thorny path for 3E challenges.* The Institute of Energy Economics, Japan (IEEJ). Retrieved from: https://eneken.ieej.or.jp/en/whatsnew/430.html

IPCC. (2014). *Climate Change 2014: Mitigation of Climate Change.* Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA Retrieved from: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc\_wg3\_ar5\_full.pdf

IRENA. (2015). *Renewable Power Generation Costs in 2014.* Abu Dhabi, United Arab Emirates: International Renewable Energy Agency, 2015. Retrieved from: http://www.irena.org/DocumentDownloads/Publications/IRENA\_RE\_Power\_Costs\_2014\_report.pdf.

IRENA. (2016). *The Power to Change: Solar and Wind Cost Reduction Potential to 202*5. International Renewable Energy Agency. Retrieved from: http://www.irena.org/DocumentDownloads/Publications/IRENA\_Power\_to\_Change\_2016.pdf

IRENA. (2018a). *Renewable Energy Benefits: Leveraging local capacity for offshore wind*. Retrieved from /publications/2018/May/Leveraging-Local-Capacity-for-Offshore-Wind

IRENA. (2019a). *Data and Statistics Dashboard.* International Renewable Energy Agency. Retrieved from: <http://resourceirena.irena.org/gateway/dashboard/?topic=4&subTopic=16>

IRENA. (2019b). *Global energy transformation:* The REmap transition pathway (Background report to 2019 edition), International Renewable Energy Agency, Abu Dhabi.

JRC. (2014). *ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050 (EUR - Scientific and Technical Research Reports).* Publications Office of the European Union. https://doi.org/10.2790/057687

Kost, C., Shammugam, S., Jülch, V., Nguyen, H.-T., & Schlegl, T. (2018). *Levelized Cost of Electricity- Renewable Energy Technologies (p. 42).* Fraunhofer Institute for Solar Energy Systems ISE. Retrieved from https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2018\_Fraunhofer-ISE\_LCOE\_Renewable\_Energy\_Technologies.pdf

Lantz, E., Wiser, R. Hand, M. (2012). *The Past and Future Cost of Wind Energy.* National Renewable Energy Laboratory, Golden, CO, Report No. NREL/TP-6A20-53510. Retrieved from: http://www.nrel.gov/docs/fy12osti/54526.pdf.

Lazard. (2016). *Lazard’s Levelized Cost of Energy Analysis – Version 10.0.* Retrieved from https://www.lazard.com/perspective/levelized-cost-of-energy-analysis-100/

Lazard. (2018). *Levelized Cost of Energy and Levelized Cost of Storage 2018, version 12.0*. Lazard. Retrieved from /perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/

Lemming, J.K., Morthorst, P.E., Clausen, N.E. (2009). *Offshore Wind Power Experiences, Potential and Key Issues for Deployment.* Forskningscenter Risø Roskilde.

Loftus, P.J., Armond M Cohen, Jane A.M., Long, J., Jenkins, J.D. (2015). A critical review of global decarbonization scenarios: what do they tell us about feasibility? *Wiley Interdisciplinary Reviews: Climate Change 6, no. 1 (2015): 93–112.*

Masanet, E, Chag, Y., Gopal, A., Larsen, P., Morrow III, W., Sathre, R., Shehabi, A., Zhai, P. (2013). Life cycle assessment of electric power systems. *Annu. Rev. Environ. Resour, 38:107–36.* Doi: 10.1146/annurev-environ-010710-100408

Nakata, T., Silva, D., & Rodionov, M. (2011). Application of energy system models for designing a low-carbon society. Progress in Energy and Combustion Science, 37(4), 462–502. https://doi.org/10.1016/j.pecs.2010.08.001

National Renewable Energy Laboratory (NREL). (2018a). *2017 Offshore Wind Technologies Market* Update | Department of Energy. Retrieved from https://www.energy.gov/eere/wind/downloads/2017-offshore-wind-technologies-market-update

National Renewable Energy Laboratory (NREL). (2018b). *2017 Wind Technologies Market Report* | Department of Energy. Retrieved from https://www.energy.gov/eere/wind/downloads/2017-wind-technologies-market-report

Navigant Research. (2015). *World Wind Energy Market Update 2015*. Burlington, MA. Retrieved from: http://www.navigantresearch.com/research/world-wind-energy-market-update-2015

NETL (2013). *Power Generation Technology Comparison from a Life Cycle Perspective.* National Energy Technology Laboratory. Retrieved from https://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Life%20Cycle%20Analysis/Technology-Assessment-Compilation-Report.pdf

NGS (2011). *Continental shelf.* In National Geographic Society. Retrieved from http://www.nationalgeographic.org/encyclopedia/continental-shelf/

NREL. (2018). *Annual Technology Baseline.* Retrieved January 3, 2019, from https://atb.nrel.gov/electricity/2018/index.html?t=lw

Principle Power. (2015). *Windfloat.* Principle Power, Inc. Retrieved from: http://www.principlepowerinc.com/en/windfloat

PwC (2010) *Meeting the 2020 renewable energy targets: Filling the offshore wind financing gap*, PricewaterhouseCoopers LLP (PwC).

Ram M., Bogdanov D., Aghahosseini A., Gulagi A., Oyewo A.S., Child M., Caldera U., Sadovskaia K., Farfan J., Barbosa LSNS., Fasihi M., Khalili S., Dalheimer B.,Gruber G., Traber T., De Caluwe F., Fell H.-J., Breyer C. (2019). *Global Energy System based on 100% Renewable Energy –Power, Heat, Transport and Desalination Sectors.* Study by Lappeenranta University of Technology and Energy Watch Group, Lappeenranta, Berlin, March 2019. Available at: <http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf>

Ram, M., Bogdanov, D., Aghahosseini, A., Oyewo, A. S., Gulagi, A., Child, M., … Breyer, C. (2017). *Global Energy System based on 100% Renewable Energy-Power Sectors. (p. 156).* Lappeenranta, Berlin: Study by Lappeenranta University of Technology and Energy Watch Group. Retrieved from: http://energywatchgroup.org/wp-content/uploads/2017/11/Full-Study-100-Renewable-Energy-Worldwide-Power-Sector.pdf

REN21. (2016). *Renewables 2016 – Global Status Report*. REN 21 – Renewable Energy Policy Network for the 21st Century. Retrieved from: http://www.ren21.net/wp-content/uploads/2016/06/GSR\_2016\_Full\_Report\_REN21.pdf

Rubin, E.S., Azevedo, I.M.L., Jaramillo, P., Yeh, S. (2015). A review of learning rates for electricity supply technologies. *Energy Policy 86, 198-218.*

Rule, B.M., Worth, Z.J., Boyle, C.A. (2009). Comparison of Life Cycle Carbon Dioxide Emissions and Embodied Energy in Four Renewable Electricity Generation Technologies in New Zealand. *Environ Sci Technol. 15;43(16):6406-13.* Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/19746744

Schmidt T. S., R. Born, and M. Schneider (2012). Assessing the costs of photovoltaic and wind power in six developing countries. *Nature Climate Change 2, 548 – 553.*

Shell International B.V. (2018). *Sky Scenario.* Shell International. Retrieved from: https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html

Sieros, G., Chaviaropolous, F., Sorensen, J., Bulder, B, Jamieson, F. (2010). Upscaling wind turbines: theoretical and practical aspect and the impact on the cost of energy. *Wind Energy 15, 3-17.*

Sovacool, B. K., Enevoldsen, P., Koch, C., & Barthelmie, R. J. (2017). Cost performance and risk in the construction of offshore and onshore wind farms. *Wind Energy, 20(5), 891–908.* https://doi.org/10.1002/we.2069

Staffell, I., & Green, R. (2014). How does wind farm performance decline with age? *Renewable Energy, 66, 775–786.* https://doi.org/10.1016/j.renene.2013.10.041

Stehly, T. J., Beiter, P. C., Heimiller, D. M., & Scott, G. N. (2018). *2017 Cost of Wind Energy Review* (No. NREL/TP-6A20-72167). National Renewable Energy Lab. (NREL), Golden, CO (United States). https://doi.org/10.2172/1475534

Thomson, C., & Harrison, G. (2015). *Assessing the life cycle costs and carbon emissions of wind power*. ClimateXChange. Retrieved from https://www.climatexchange.org.uk/research/projects/assessing-the-life-cycle-costs-and-carbon-emissions-of-wind-power/

Tsiropoulos, I., Tarvydas, D., & Zucker, A. (2018). *Cost development of low carbon energy technologies: Scenario-based cost trajectories to 2050*, 2017 edition - EU Science Hub - European Commission. Retrieved December 11, 2018, from: https://ec.europa.eu/jrc/en/publication/cost-development-low-carbon-energy-technologies-scenario-based-cost-trajectories-2050-2017-edition

U.S. D.O.E (2015). *2015 Wind Technologies Market Report*. U.S. Department of Energy. Retrieved from: http://energy.gov/sites/prod/files/2016/08/f33/2015­Wind­Technologies­Market­Report­08162016.pdf

UNDESA. (2015). *World Population Prospects: The 2015 Revision*. United Nations Department of Economic and Social Aﬀairs, Population Division, United Nations, New York. Retrieved from: https://esa.un.org/unpd/wpp/

van der Zwaan, B., Rivera-Tinoco, R., Lensink, S., & van den Oosterkamp, P. (2012). Cost reductions for offshore wind power: Exploring the balance between scaling, learning and R&D. *Renewable Energy, 41, 389–393*. https://doi.org/10.1016/j.renene.2011.11.014

WEC. (2013). *World Energy Perspective: Cost of Energy Technologies*. New York, NY: Bloomberg New Energy Finance. Retrieved from: http://www.worldenergy.org/wp-content/uploads/2013/09/WEC\_J1143\_CostofTECHNOLOGIES\_021013\_WEB\_Final.pdf

Wiser, R. Bollinger, M. (2014). *2013 Wind Technologies Market Report.* Oak Ridge, TN: Lawrence Berkeley National Laboratory. Retrieved from: http://emp.lbl.gov/sites/all/files/2013\_Wind\_Technologies\_Market\_Report\_Final3.pdf

Wiser, R., Jenni, K., Seel, J., Baker, E., Hand, M., Lantz, E., & Smith, A. (2016). Expert elicitation survey on future wind energy costs. *Nature Energy, 1, 16135.* doi: http://dx.doi.org/10.1038/nenergy.2016.135

Wiser, R., Yang, Z. (2011). *Chapter 7: Wind Energy.* In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, UK: Cambridge University Press. Retrieved from: <http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch07.pdf>

# Glossary

**Adoption Scenario** – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance, a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in the use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate the high growth of the solution.

**Approximate PPM Equivalent** – the reduction in the atmospheric concentration of CO2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

**Average Abatement Cost** – the ratio of the present value of the solution (**Net** **Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario** and is used to build the characteristic “*Marginal Abatement Cost*” curves when Average Abatement Cost values for each solution are ordered and graphed.

**Average Annual Use** – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, the total number of passenger-km driven by a hybrid vehicle in a year depends on the country and the typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

**Cumulative First Cost** – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Direct Emissions** – emissions caused by the operation of the solution, which are typically caused by the lifetime use of the solution. They should be entered into the model normalized per functional unit.

**Discount Rate**- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account, not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

**Emissions** **Factor**– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO2e/kWh.

**First Cost**- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

**Functional Unit** – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high-speed rail provides billions of passenger-km of mobility.

**Grid Emissions** – emissions caused by the use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

**Implementation Unit** – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV’s in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

**Indirect Emissions** – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

**Learning Rate/Learning Curve** - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service is provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a good drops by 2% every time total production doubles.

**Lifetime Capacity** – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

**Lifetime Operating Savings**–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

**Lifetime Cashflow NPV**-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

**Marginal First Cost** – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Net Annual Functional Units (NAFU)** – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

**Net Annual Implementation Units (NAIU)** – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

**Net Operating Savings** – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

**Operating Costs** – the average cost to ensure the operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

**Payback Period** – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

**PDS/ Project Drawdown Scenario** – this is the high growth scenario for the adoption of the solution.

**PPB/ Parts per Billion** – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

**PPM/ Parts per Million** – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

**REF/ Reference Scenario** – this is the low growth scenario for the adoption of the solution against which all **PDS scenarios** are compared.

**Replacement Time**- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

**TAM/ Total Addressable Market** – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents the world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

**Total Emissions Reduction** – the sum of the grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

**Transition solutions** - are considered till better technologies and less impactful are more cost-effective and mature.

**TWh/ Terawatt-hour** – A unit of energy equal to 1 billion kilowatt-hours.

1. Current adoption is defined as the amount of functional demand supplied by the solution in 2018. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated. [↑](#footnote-ref-1)
2. Only Arent *et al.* (2014) include biomass as renewable energy. [↑](#footnote-ref-2)
3. Current adoption is defined as the amount of functional demand supplied by the solution in the base year of study. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated. [↑](#footnote-ref-3)
4. In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary. [↑](#footnote-ref-4)