**Technical assessment for**

**Onshore Wind Turbines**

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Table of Contents

[List of Figures 4](#_Toc18958301)

[List of Tables 4](#_Toc18958302)

[Acronyms and Symbols Used 5](#_Toc18958303)

[Executive Summary 7](#_Toc18958304)

[1 Literature Review 8](#_Toc18958305)

[1.1. State of Onshore wind energy technologies 8](#_Toc18958306)

[1.2. Adoption Path 13](#_Toc18958307)

[1.2.1 Current Adoption 13](#_Toc18958308)

[1.2.2 Trends to Accelerate Adoption 14](#_Toc18958309)

[1.2.3 Barriers to Adoption 15](#_Toc18958310)

[1.2.4 Adoption Potential 16](#_Toc18958311)

[1.3 Advantages and Disadvantages of Wind Onshore 18](#_Toc18958312)

[1.3.1 Similar Solutions 18](#_Toc18958313)

[1.3.2 Arguments for Adoption 18](#_Toc18958314)

[1.3.3 Additional Benefits and Burdens 19](#_Toc18958315)

[2 Methodology 23](#_Toc18958316)

[2.1 Introduction 23](#_Toc18958317)

[2.2 Data Sources 24](#_Toc18958318)

[2.3 Total Addressable Market 26](#_Toc18958319)

[2.4 Adoption Scenarios 27](#_Toc18958320)

[2.4.1 Reference Case / Current Adoption 27](#_Toc18958321)

[2.4.2 Project Drawdown Scenarios 28](#_Toc18958322)

[2.5 Inputs 29](#_Toc18958323)

[2.5.1 Climate Inputs 29](#_Toc18958324)

[2.5.2 Financial Inputs 30](#_Toc18958325)

[2.5.3 Technical Inputs 31](#_Toc18958326)

[2.6 Assumptions 32](#_Toc18958327)

[2.7 Integration 33](#_Toc18958328)

[2.8 Limitations / Further Developments 33](#_Toc18958329)

[3 Results 35](#_Toc18958330)

[3.1 Adoption 35](#_Toc18958331)

[3.2 Climate Impacts 36](#_Toc18958332)

[3.3 Financial Impacts 38](#_Toc18958333)

[4 Discussion 40](#_Toc18958334)

[4.1 Limitations 41](#_Toc18958335)

[4.2 Benchmarks 41](#_Toc18958336)

[5 References 43](#_Toc18958337)

[6 Glossary 51](#_Toc18958338)

# List of Figures

[Figure 1.1 - Levelized cost of energy (LCOE) for wind power compared to other technologies (Adapted from IRENA, 2018) 11](#_Toc23603798)

[Figure 1.2 - Global annual average power output for wind power compared to other technologies [Adapted from IEA WEO (2018)] 12](#_Toc23603799)

[Figure 1.3 – Wind Capacity projections from the IEA ETP 2016 in their 2DS (2ºC scenario) 16](#_Toc23603800)

[Figure 1.4 - Wind Power capacity long-term market projections until 2030 (Adapted from Greenpeace, 2015) 17](#_Toc23603801)

[Figure 3.1 World Annual Adoption 2015-2060 36](#_Toc23603802)

[Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction 2015-2060 38](#_Toc23603803)

# List of Tables

[Table 1.1 Conventional versus wind technologies: some key impacts 21](#_Toc17934222)

[Table 2.1 Climate Inputs 29](#_Toc17934223)

[Table 2.2 Financial Inputs for Conventional Technologies 31](#_Toc17934224)

[Table 2.3 Financial Inputs for Solution 31](#_Toc17934225)

[Table 2.4 Technical Inputs Conventional Technologies 32](#_Toc17934226)

[Table 2.5 Technical Inputs Solution 32](#_Toc17934227)

[Table 3.1 World Adoption of the Solution 35](#_Toc17934228)

[Table 3.2 Climate Impacts 37](#_Toc17934229)

[Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq 37](#_Toc17934230)

[Table 3.4 Financial Impacts 39](#_Toc17934231)

[Table 4.1 Benchmarks 42](#_Toc17934232)

# 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 (onshore)* as onshore utility-scale wind power technologies. This solution replaces conventional electricity-generating technologies such as coal, oil, and natural gas power plants. After slow but steady growth, wind capacity has increased around one-fifth per year for the past decade. In 2018, global cumulative installed onshore wind capacity was 539.6 GW (IRENA, 2019), dominated by China (35%), followed by the United States (17%), Germany (10%), India (6%), Spain (4%) (GWEC 2018). A “next generation” phase of deployment is already emerging, where the onshore wind is technologically mature and economically affordable.

The total addressable market for *wind turbines (onshore)* is based on projected global electricity generation in terawatt-hours till 2050, with current adoption (i.e. 2018) estimated at 5.09 percent (i.e. 1,148 terawatt-hours) of generation. Impacts of increased adoption of wind turbines (onshore) 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. Plausible Scenario is based on the evaluation of four global energy systems models’ scenarios, following a high growth trajectory, and capturing 19.8 percent of the electricity generation market share in 2050. Drawdown and Optimum Scenarios follow a more aggressive adoption pathway aligned with three scenarios from Greenpeace, Ram *et al* and Ecofys, that project 100% RES electricity generation by 2050, resulting in a 26,9 percent share of the market in 2050.

Through the process of integrating onshore wind turbines 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.

The results of the *Plausible* Scenario show that the marginal first costs compared to the *Reference* Scenario would be US$911 billion from 2020-50, with over US$2.05 trillion in operation savings over the same period. Increasing the use of onshore wind from 5.09 percent in 2018 to 19.8 percent of world electricity generation by 2050 would require an estimated US$4.58 trillion in cumulative first costs. With its low greenhouse gas emissions, under the *Plausible* Scenario, onshore wind turbines could reduce 48.7 gigatons of carbon dioxide-equivalent emissions from 2020-2050. Both the *Drawdown* and *Optimum* Scenarios are significantly more ambitious, with emission reductions over 2020-2050 of 148.2 gigatons of carbon dioxide-equivalent in the *Drawdown* and 147.1 in the *Optimum* scenario.

Wind power plays a large and essential role in any long-term projections of 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 backup power or storage at certain times to meet electricity demand. The increased use of wind and solar may require investments and improvements in grid infrastructure and the flexibility of power systems. such as production credits and tax breaks.

# Literature Review

## State of Onshore wind energy technologies

Wind is the movement of air from an area of high pressure to an area of low pressure, due to the uneven heating of the Earth's surface by the sun (Wang et al., 2004). As hot air rises, cooler air moves in to fill the void. This kinetic energy can be harnessed with a turbine to produce mechanical energy and electricity. The Earth’s rotation and geographic features affect both location and nature of the winds, although advances in wind turbines is allowing to take advantage of lower levels of wind in more regions.

Windmills have used wind as a resource for food and water production since the eleventh century. By the late 1800s wind was successfully used to generate electricity, though the use of wind for electricity generation at a commercial scale did not significantly grow until the 1970s and 80s in the light of uncertainty over oil supplies and the safety of nuclear power. Technical advances and government support aided the early development of the wind energy industry, particularly in Denmark, California, Germany, and Spain.

The development of commercial scale wind turbines have mostly occurred on horizontal-axis design with three blades capturing the wind upwind of the tower. The rotor and blades are connected to a hub and main shaft through which mechanical energy is transferred to a gearbox and generator, where the energy is converted to electricity (Turkenburg *et al*., 2012). These components are contained in fiberglass, called a nacelle, which protects the components from the elements. The nacelle is mounted on a tower to allow the rotor to capture higher-quality wind resources than found near the ground. Wind turbines are typically grouped together into wind power plants or farms with up to hundreds of megawatts of capacity, with the electricity linked to the utility transportation system grid (Turkenburg *et al*., 2012).

The amount of power generated by a wind turbine is mostly determined by the size and capacity of the turbine and the intensity of the wind resource. Manufacturers are trying to maximize blade lengths and aerodynamics, while minimizing weight, to achieve highest capacity factors at lower cost. The general trend is to develop larger machines creating a better economy of scale with longer blades, larger rotor size and higher hub heights to allow for an increase output and reach stronger winds. The reason for this is that the costs associated with foundations, road building, electricity grid connection, some components embedded in wind turbines (the electronic control system, etc.), and maintenance costs are largely independent of size. Also, a large turbine with a tall tower uses the existing wind resource more efficiently. The swept are of the turbine rotor, in addition to wind speeds, determines how much energy could be harvested from wind per annum.

In order to take advantage of wind as a resource for electricity generation a minimum average wind speed is needed of around 3-4 m/s, rated power generation is reached at around 10 to 12 m/s wind speed and maximum operational wind speed: approximately 25 m/s (DEA and Energynet, 2012).

Average capacity factors of wind turbines are a result of higher hub heights and larger swept areas, though, capacity factors are also driven by the overall quality of the wind resource at the site, its variability, and the flexibility of the local electrical system in preventing curtailment of wind use. Although wind turbines are increasing in size and height to harvest more wind, this appears to be somewhat counter-balanced by their increased sitting in areas of lower wind resources.

Data registries for the USA show that capacity factors were about 30% for 2000 to 2005, and 35% for 2006 to 2015. Outside of the US, weighted average capacity factors differ by region, from close to 24% in China and India to 43% in Brazil. The capacity factor ranges for Africa and South America (excluding Brazil) are similar to those in the US (IRENA, 2105). Although the capacity factors are lower in India and China, the capital expenditure costs per kilowatt are also lower; conversely, while Brazil on average harnesses more wind energy from its wind farms, the costs are also higher (IRENA, 2015).

Currently, a utility-scale wind turbine has about 8,000 parts (GWEC, 2017) with the major cost drivers being the tower, turbine blade, and the nacelle or brain components. The nacelle houses or mounts some of the components including gearbox, power converter, shaft, electrical generator, anemometer and wind vane. Wind turbines (including towers and installation) are the main cost item for onshore wind project, typically accounting for around 60% (BNEF, 2013) and sometimes up to 80% (IRENA, 2015) of the total installed cost for a wind farm. Remaining capital costs are mainly for grid connection, project development, and permitting (DOE, 2015).

Costs also depend widely on wind resource availability, regulatory and fiscal framework, the cost of capital, import logistics/duties, and other local influences. From the 1980s to the early 2000s, average capital costs for onshore wind declined sharply. In the United States, capital costs were at their lowest level from roughly 2001 to 2004, approximately 65% below costs from the early 1980s (Lantz *et al*., 2012). Historical capital cost reductions were coupled with increased performance from more advanced components and bigger turbines (Wiser and Yang, 2011). The combined effects of falling costs and enhanced performance dramatically reduced the levelized cost of electricity (LCOE) for onshore wind energy, from upwards of $150/MWh in the 1980s and 90s to about $50/MWh in the early 2000s (Lantz et al., 2012). Figure 1.1 shows that the LCOE of onshore wind falls within the lower band of the LCOE range of fossil-fuel fired electricity generation. This indicates that onshore wind is on track to grid parity without subsidy support.

Capital cost increases began rising from 2004 to 2009, as turbines became more expensive due to a rise in materials and energy prices, as well as growing demand (BNEF, 2014). Wind turbine manufacturers were also introducing longer and higher-cost turbines, with taller towers and more capital-intensive foundations; however, these new turbines also achieved larger capacity factors and expanded the availability of wind energy to areas with lower wind resources, often closer to areas of higher energy demand (Lantz *et al.,* 2012). Also, these turbines made it possible to exploit wind energy in difficult terrains and difficult locations. An exception to this general trend of rising capital costs was China, due to the emergence of low-cost and state-aided domestic equipment manufacturers (IEA, 2013).

Since 2009 onshore wind project capital costs have declined while performance improvements have continued. 2013 data depicted that total installed costs in the USA have decrease from around US$2,300/kilowatts (kW) in 2009 to US$1,657/kW in 2013, a 28% fall from peak prices and a much quicker decline in costs than many had forecasted (Wiser and Bollinger, 2014). Installed costs in China and India between 2011 and 2014 were the lowest in the world, averaging US$1,310/kW in China and US$1,370/kW in India (IRENA, 2015).

Total installed costs and weighted averages of commissioned and proposed wind farms are different across countries and regions for 2013-2014. On the higher end, the average installed cost of wind farms was US$2,210/kW in Africa, US$2,110/kW in Oceania, and US$2,200/kW in South America, excluding Brazil, where average costs are greater but capacity factors also tend to be higher. Costs are lower in the US at US$1,657/kW and Eurasia at US$1,710/kW. Average installed costs in China between 2013 and 2014 were the lowest in the world, averaging US$1,310/kW, followed by India, at an average of US$1,370/kW (IRENA, 2015).

From the 2015 first costs presented by REN 21 (2016) it can be seen a significant cost reduction trend at a yearly basis around the world, with a world average of US$1,233/kW. Africa with US$2,078/kW; Middle East with US$2,494/kW depict the highest levels of costs, EU, US and Latin America around US$1,800-1,900kW; and once again China and India with the lowest costs US$1,250kW and US$1,227kW respectively. The decreased costs in China and India can be traced to their low-cost local manufacturing bases, including low materials and labor costs, as well as policy support for deployment.

Regarding operation and maintenance (O&M) costs the available data shows a considerable spread, demonstrating that O&M costs and how they are reported by respondents are not uniform across projects. An example is disclosed by DOE (2016) where financial statements of EDP Renováveis (EDPR), company that owned more than 4 GW of U.S. based wind project assets at the end of 2015, indicated higher total operating costs of $0.025/kWh for its onshore wind portfolio. Which was twofold ~$0.01/kWh average O&M cost reported for the 93 projects in the Berkeley Lab data sample installed since 2000. This disparity in O&M between EDPR and the Berkeley Lab data sample is drawn by differences in the scope of expenses reported (DOE, 2016).

However, the literature suggest that projects installed within the past decade have, on average, incurred lower O&M costs than those previously installed. According to DOE (2016), the drop in O&M costs was due to at least two factors: 1) O&M costs generally increase as turbines age, component failures become more common, and manufacturer warranties expire; and 2) projects installed more recently had larger turbines and improved designs, therefore experiencing lower O&M costs on a per-kWh basis (DOE, 2016). Thus, reported average values for operation and maintenance costs for onshore wind are around US$0.01 to US$0.03/kWh (IPCC, 2014; IRENA, 2016; DOE, 2016).

Figure 1. - Levelized cost of energy (LCOE) for wind power compared to other technologies (Adapted from IRENA, 2018)

In terms of generation, onshore wind global average annual electricity output is twice that of solar PV as shown in Figure 1.2 below. This difference in the energy output can be attributed to higher capacity of wind power (turbine size), due to increased turbine hub height and sophistication.

Figure 1. - Global annual average power output for wind power compared to other technologies [Adapted from IEA WEO (2018)]

Wiser *et al*. (2016) shows that LCOE reduction has been largely driven by four factors including learning with market growth (efficiency improvement), research and development (innovations), increased competition and decreased risk, eased wind project and transmission siting (decreased development costs and higher capacity factor).

In literature, the levelized cost of energy (LCOE) metric has been used based on assumptions of a scenario in which lifetime revenues equal costs, a fixed weighted average cost of capital (WACC) applies, full economic life of the project, and absence of tax responsibilities. However, feed-in tariff (FiT) and power purchase agreement (PPA) prices are based on market and policy-specific context of the contract where the assumptions made for the calculation of LCOE may not hold true. For instance, a feed-in law or PPA contract may assume a shorter project’s economic life in awarding payments. Also, the WACC and tax considerations in PPA contract may not match that for LCOE calculation. The implication is that LCOE cannot be used as a proxy for final FiT and PPA prices without first matching the underlying assumptions.

## Adoption Path

### Current Adoption

The amount of new wind power has grown steadily, particularly in the past decade, led by the European Union, US, and China (BP 2014), with annual capacity increase consistently higher year after year. In Europe, encouraging policy incentives were the early drivers for the wind uptake. Nonetheless, since 2009 more than three-quarters of the annual capacity installed was outside Europe and this trend is likely to continue (Greenpeace, 2015).

In 2015, the power sector have seen its largest annual increase in capacity ever, with significant growth around the different regions. World cumulative installed capacity of renewable energy sources (RES) was 1,849 GW (including hydro) in 2015, with 433 GW from wind power (*i.e.* 22% increase from 2014). Wind power was the leading source of new power-generating capacity in Europe and in the United States in 2015, and the second largest in China (REN21, 2016). Cumulative installed wind capacity has increased by approximately 20% per year for the past decade.

During 2015, wind was the most cost-effective option for new grid-based power in multiple regions as Canada, Mexico, New Zealand, South Africa, Turkey, and regions of Australia, China, and the USA (REN21, 2016). The weighted average LCOE for onshore wind in 2015 ranged from very low levels of 25-30 US$/MWh (tender bid in Morocco to be in operation between 2017-2020) (REN21, 2016) to 60 US$/MWh in China and Asia and 80 US$/MWh in Africa. North America also has very competitive wind projects, with a weighted average LCOE of US$70/MWh (IRENA, 2015). U.S. DOE (2015) presents lower values for the United States, with nearly all PPA coming in at below $40/MWh, with some below $20.

A “next generation” phase of implementation is rising, as onshore wind and also solar photovoltaics become technologically mature and financially attractive. At the end of 2017, China has both the largest amount of cumulative installed wind capacity at 188 GW (35%), and the largest new capacity additions at 19.5 GW (37%) within 2017. It is followed by the USA (89 GW), Germany ( 56 GW), India (33 GW), and Spain (23 GW) as at December, 2017 (GWEC, 2018). New markets emerged across Africa, Asia, and Latin America, where the first large-scale wind farms were installed in Guatemala, Jordan, Serbia and Samoa (REN21, 2016). In Morocco - North Africa, Siemens Gamesa Renewable Energy (SGRE) established the first wind-turbine blade manufacturing plant to bring its services closer to new markets in Africa and Middle East, and to consolidate on its 2.1 GW installed capacity market share in Africa.

In Europe, repowering existing wind farms is already happening. Along with the substitution of old turbines with fewer, larger, taller, and more efficient and reliable machines, some operators are swapping pretty new machines for upgraded turbines that include software improvements increasing capacity factors of those wind farms. At least 300 turbines with around 300 MW were disassembled and upgraded in European countries, two turbines (0.7 MW) in Japan and one unit (2 MW) in Australia. Germany is identified as the largest market for repowering due to the age of their current installed wind power infrastructures (REN21, 2016). Study has shown that onshore wind farm output in the UK decline at an average of 1.6% per year due to ageing-related availability and tear, and there are indications that new models of wind turbine decline in output less rapidly as they age (Staffell and Green 2014). The implication of this decline is that onshore wind power becomes expensive with ageing due to fall in capacity factor, making a business case for repowering to keep the wind farm operation safe and profitable. The repowering market is not yet huge, and the Global Wind Energy Council (GWEC) estimate shows that only about 14% of the cumulative installed capacity of 540 GW has been built over a decade ago. This 14% represents a total of 74 GW which are may be repowered in the next decade to 15 years. The production tax credit (PTC) scheme in the United States is driving repowering of old wind farms, and the US may likely supplant Germany as the top repowering market in the near future. The PTC incentive is also one of the drivers for the faster learning of onshore wind costs in the United States.

### Trends to Accelerate Adoption

In recent years, the combination of decreasing trends of LCOE and increased performance of onshore wind technologies fostered the increase adoption of wind turbines. With towers getting taller and blades getting bigger, their capacity factors rise. These developments have allowed wind LCOE to be within the same cost range as fossil fuels generation technologies even without accounting for externalities in many markets (e.g. Mexico, China, US) (REN21, 2016), and often lower when external costs are considered (IRENA, 2015). In 2016 and subsequent years, expectations of further cost reductions were depicted by record-low winning bids in power auctions in India, Latin America (i.e. Brazil), Middle East and North Africa (*i.e.* Morocco).

Thus, new onshore wind power capacity is projected to continue growing steadily with or without climate policies, showing that the technology is increasingly mature and cost-competitive with fossil fuels. However, wind deployment could be accelerated by renewable energy and portfolio standards that mandate a certain level of renewable use. Wind developers 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. Technology knowledge transfer could also help spread wind power across borders.

### Barriers to Adoption

Increased adoption of wind onshore systems need extended and improved grid connections, with increased transmission support and storage technologies to allow for increasing integration of Variable Renewable Energy (VRE) including wind and solar electricity. This issue could also 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.

Multiple grid modeling and integration 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).

Electricity output from wind farm varies with wind resource availability and climate regimes at the site. This variability necessitates the need for back-up capacity to balance shortfalls in anticipated power output and maintain the security of power systems. The need for back-up capacity introduces additional cost consideration for wind power deployment and in recent years, back-up and balancing for wind power has been more problematic than other renewable power technologies.

The integration of wind power is generally faced with three key challenges, including:

* Accurate production forecasts – to plan the dispatch of backup systems to ensure that power generation matches demand during low wind speed, and/or strategies to sustain the value of wind power during the times of high wind speeds.
* Capacity adequacy – more wind capacity penetration makes conventional power plants less attractive, and thus less need for base load. However, in times of low or no wind the just ‘un-attractive’ power plant becomes needed as peak load generation. The implication is the need for electricity market re-structuring to make it attractive to dispatch conventional power plants as peaking load.
* Grid considerations – to minimize curtailment and grid congestion issues. Wind power generation is variable, and often takes place at locations that are both sparse and far from the load centers. These justify the need for a long-distance robust grid and the wind turbine possessing grid-supportive characteristics.

### Adoption Potential

Wind technologies are projected by several sources to be one of the most relevant technologies in future energy systems (especially onshore wind turbines). The results from International Energy Agency in their last Energy Technology Perspectives (IEA, 2016b) estimate global wind power capacity continuing to grow steadily with or without strong climate policies, reaching 1,628 GW in 2050 in the lowest mitigation scenario (*i.e.* 6DS) and 2,800 GW in the 2DS; representing 12% to 20% of total electricity generation installed capacity (Figure 1.3). This level of capacity results in approximately 4,226 TWh of electricity generated from wind (both onshore and offshore) in the 6DS, and 7,300 TWh in the 2DS scenario. In addition, only onshore wind and solar PV are on track to reach the 2DS target (IEA ETP, 2017).

Figure 1. – Wind Capacity projections from the IEA ETP 2016 in their 2DS (2ºC scenario)

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 discloses 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 1.4 compares the long-term market projections for wind power of reports from 1999 to 2014 where it can be seen the range of projections for wind deployment dependent on the year of publication and scenarios assumptions.

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

Figure 1. - 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, it was 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 Onshore

### Similar Solutions

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 onshore utility scale, there are alternative renewable energy technologies with a difference in the level of agency (e.g. buildings level) or location (i.e. offshore).

* **Wind Offshore:** offshore utility-scale wind power technologies either installed in the bottom of the sea or floating devices.
* **Micro Wind Turbines:** electricity-generating wind turbines with a 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. Microturbines can also be placed on large structures, such as skyscrapers, to take advantage of stronger, steadier breezes.

### Arguments for Adoption

Due to its low life cycle assessment (LCA) greenhouse gas emissions (GHG), wind power is crucial to decarbonize the electricity generation sector. Indeed, wind power plays a large and essential role in any modeling exercise of a low-carbon future for the following reasons: 1) wind has large megawatt capability, 2) the output of wind and solar is complementary in many regions of the world (Loftus *et al*., 2015; IEA, 2016a), 3) the resource is spread across the world, 4) and the LCOE is competitive.

As a RES, 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 power 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 onshore installations will in most cases be deployed to replace fossil fuel power plants, the 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 onshore lifecycle emissions and the variability that may come with a high penetration of wind electricity in future grids (IEA, 2014).

The environmental impacts of onshore wind compared to fossil-based power generation is relatively small. Also, among renewable power generation solutions, onshore wind has one the lowest carbon intensity per unit of electricity generated. Onshore wind has a very low but non-zero lifecycle emissions in the range 2-25 gCO2-eq/kWh, and up to 106 gCO2-eq/kWh in locations such as Scotland where significant numbers of wind farms are built on peatlands (Thomson and Harrison, 2015).

To assess a holistic environmental impacts of wind power, the life cycle assessment (LCA) approach has been used in literature. Several sources in literature conducted LCA in comparison with other clean energy solutions and conventional power generation technologies, and in all the studies, onshore wind consistently gives low emissions per unit of power generated. The strength of LCA approach lies in the consideration of not only the direct emissions associated with onshore wind farm activities from turbine/components manufacturing, installation, operation, and to decommissioning, but also the materials and resource consumption in the entire value-chain and lifetime of the project from the manufacturing gate to the farm. The phases of onshore wind power deployment often captured in the LCA include: turbine/component manufacturing and construction, transport to test facilities and to site, on-site installation, operation and maintenance, and decommissioning. Among these, the turbine/component manufacturing and construction is the main driver of GHG emissions in onshore wind power. In the manufacturing/construction stage, the tower and nacelle manufacturing, foundation, and the eventual grid integration contribute the bulk of the GHG emissions with only a marginal contribution from turbine blade manufacturing.

### Additional Benefits and Burdens

Wind power is less constrained by location than other renewable technologies such as hydro and geothermal, particularly as advances in technology help wind turbines be accessible to more areas. This can result in reducing grid costs and distribution losses (IEA; 2016b). For Nakata *et al.* (2011), in areas where there is wind energy potential, but no connection to the grid, wind turbines are also suitable option because of their simplicity of design and higher efficiency. Since wind is an irregular resource, off-grid applications generally require some form of electricity storage. Furthermore, hybrid wind-diesel systems and biomass-fired steam boilers with turbine-generators can replace or supplement existing diesel and gasoline generators, resulting in better environmental and economic performance (Nakata *et al.*,2011).

However, wind power may still require investment if transmission and distribution lines to transfer the electricity to high demand areas is needed. Wind used along with solar may have additional costs for grid infrastructure, although renewable proponents argue the issue and costs have been overstated (AWEA, 2014; IRENA, 2015; IEA, 2016a).

Since wind turbines do not cover the entire area in which they are located therefore they are compatible with other land uses, such as agriculture and foraging. Despite their several advantages, there is a concern about possible disruption of wildlife habitats with impacts of wind farms on birds, bats, and other wildlife populations; the local environment with land erosion; the landscape; and communities and individuals living near wind projects due to turbines rotation noise (Nakata et *al*., 2011; DOE, 2015). This is particularly true as turbines increase in size and proximity to more populated areas. Continued research, technological solutions (*e.g.* strategic operational strategies and wildlife deterrents), and experience can make sitting and mitigation more effective and efficient (DOE, 2015).

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. Where turbines do require decommissioning, the salvage value often offsets the costs (Wiser and Yang, 2011).

According to REN21 (2016) onshore wind power face some challenges in the lack of transmission infrastructure, delays in grid connection, the need to re-route 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. Yet many countries and regions continue to add large amounts of wind to their system, such as Denmark, which uses wind to meet up to 40% of national demand (Navigant, 2015) and between 20% to 30% of Portugal, Ireland, and Spain’s demand (DOE, 2016).

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 levels (Arent *et al.*, 2014, Budischak *et al.*, 2013, Hart and Jacobson 2011).[[1]](#footnote-1) Wind along with solar often provides most of the energy demanded, backed-up by natural gas turbines and pumped hydro storage.

Another concern with wind electricity generation, like solar, is intermittency. Wind speeds vary on a seasonal and hourly basis, requiring backup power or storage at certain times to meet electricity demand, and maintain the security of electricity grid. 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 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, IRENA (2015) estimates the resulting grid costs for transmission networks tend to be less than around US$0.013/kWh.

The cost component of increased wind and solar capacity can be reduced by peak shaving, through demand-side management, as well as stronger and more flexible electricity grids. The integration costs of these technologies are also less applicable to areas that are still building up a centralized electricity system (as southeast Asia and African countries). Remote areas may also benefit from a more distributed electricity system (IRENA, 2015).

All these advantages of wind turbines linked with its year by year reducing costs, increased capacity factors and low LCA GHG emissions makes it a very promising solution for long-term climate mitigation. 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 |
| *Labour 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 onshore systems. The models used for this analysis construct both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for wind onshore. 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 onshore remains fixed at the current adoption (i.e. 2018) percentage of Total Addressable Market (TAM), estimated at 5.09 percent (1,148 terawatt-hours) of electricity generation (PD estimation). The TAM for this 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 onshore 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, 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 RRS model to evaluate the adoption of wind onshore 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 solution variable, it is conducted a sensitivity analysis of, on average, 26 data points reported in the literature and in some cases as many as 56. This allows calculating 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.

For the global adoption scenarios, and building upon the 16 scenarios form external sources (AMPRE (2015), Greenpeace (2014, 2015) and IEA (2016))already collected for the 2017 analysis, it were newly selected eight sources with other sixteen scenarios to be potentially used: including: IEA (2018) World Energy Outlook 2018 (Current Policy, New Policy, and Sustainable Development scenarios); IEA (2017) Energy Technology Perspectives (Reference Technology, 2 Degrees, and Beyond 2 Degrees scenarios); Equinor (2018) Energy Perspectives (Rivalry, Reform, and Renewal scenarios); Grantham/Carbon Tracker (2017) Report (moderate fossil fuel intensive or NDC\_PE\_EV\_Medium, and least fossil fuel intensive or Strong\_PV\_EV\_Medium); IEEJ (2018) Outlook 2019 (Reference and Advanced Technology scenarios); Ram et al (2019) 100% Renewable Energy scenario; and 2018 Ecofys 100% 1.5ºC scenario.

These scenarios are projections of the role of onshore wind energy technologies on the future global electricity generation mix related to different climate mitigation pathways or RES adoption from 2018 to 2060. The scenarios are grouped in the RRS Drawdown model to be included under the Baseline, Conservative, Ambitious and 100%RES by 2050 cases.

Several hundred lifecycle assessments (LCAs) have been conducted for wind power technologies across the globe over the last 30 years (*e.g.* Masanet, *et al*., 2013). 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).

Recently published GHG emission estimates for wind onshore power have ranged from 2 to 56 g CO2eq/kWh over their lifetime (*e.g.* Masanet et *al*., 2013). Thomson and Harrison (2015) reported 2 to 25 g CO2eq/kWh, and up to 106 g CO2eq/kWh where onshore wind farm leads to the release of peatland’s carbon stores. The wide span in results for onshore wind reflects different assumptions around capacity factor, conversion efficiency, operating lifetime and quality of wind resource (Masanet *et al*., 2013), and how the recycling credits allocation is done (Thomson and Harrison, 2015). The US National Renewable Energy Laboratory (NREL) has attempted to reduce the variability in LCA results by harmonizing assumptions. An average lifetime of 20 years and capacity factor of 30% for onshore was combined with current IPCC GWPs, resulting in a significantly smaller range of GHG emission estimates in more recent estimates for wind power systems: 8 to 25 g CO2eq/kWh, with an average of 17 g CO2eq/kWh (*e.g*. Hertwich et *al.*, 2015 and Garcia Gusano et *al.*, 2016). This is true for both on- and offshore wind technologies, suggesting the two technology types may not have significantly different life cycle GHG emissions.

Current 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. A study for onshore wind turbines in the United Kingdom found the majority lasted 25 years before needing an upgrade (Staffell and Green, 2014), although further research is needed to assess if this lifetime reflects the global average.

The developments of wind technologies, as well as the scale and availability of the global resource, unfold that wind energy will surely play a significant future role in future power systems, especially in the context of global efforts to GHG emissions mitigation. However, the share of its contribution, as well as all the other RES, is still uncertain due to the costs.

The historical and future costs development of onshore wind technology has been studied in literature using learning curve approach. On the other hand, the use of 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 consider as principle that increases in the cumulative production of a technology lead 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, learning rates for renewables are expected to continue making the technologies more competitive, and ultimately cheaper than conventional sources, as is the case already in many markets. It is consensual that installation costs for wind turbines will continue to decline rapidly. Citi GPS (2015) presents a wind learning rate of 6.7% until 2020, with a year on year reduction of 1% and estimates until 2040 where it is considered that it will be a financial advantage and a benefit in installing RES than a cost to society.

Engineering models (*e.g.* Sieros *et al*., 2010) provide a bottom-up, technology-rich complement to learning analysis, involving detailed modeling of specific technology advancements and frequently consider both cost and performance providing a better understanding of LCOE trends. Though, for Wiser *et al.* (2016), they do not provide insights into the probability of different outcomes.

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. However, experts anticipate bigger absolute reductions (and more uncertainty) in the LCOE of offshore wind compared with onshore wind, and a narrowing gap between fixed-bottom and floating offshore costs, with an especially big expected reduction in the LCOE of floating offshore wind between 2020 and 2030 8Wiser *et al.*, 2016).

According to this study, the two leading drivers for cost reductions for onshore wind are related to rotors, which confirms earlier survey results highlighting capacity factor improvements, as does the third-ranked item, increased hub heights (Wiser *et al.,* 2016). Looking at global wind power costs from 1982 to 2013, Wiser and Bollinger (2014) calculated a learning rate of 7%, also used by the IEA in its forecast for onshore wind (IEA, 2013). Rubin *et al.* (2015) presented a review of learning rates for electricity supply technologies depicting a mean learning rate of onshore wind of 12%.

## 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 (2018) 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 onshore has increased from 177,747 MW in 2010 to near 540,000 MW in 2018, more than doubling in total installed capacity (IRENA, 2019), thus it is a significant challenge to project global wind onshore 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[[2]](#footnote-2) (in percent) of the market. Historical data of onshore wind generation from 2014 to 2017 was retrieved from IRENA (2019) and 2018 was estimated by PD representing 5.09% of total generation. That is, the current percentage of total electricity generation (TWh) provided by wind onshore 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 2018. 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 each solution (i.e. wind onshore), to compare the impact of an increased adoption of the solutions 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 onshore wind turbines, this scenario is based on the evaluation of yearly averages of four optimistic scenarios: 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.

#### 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 wind onshore, this scenario 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. These scenarios represent very ambitious pathway towards a fully decarbonized energy system in 2050.

#### 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. Like the *Drawdown* Scenario, this scenario for wind onshore 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 onshore 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 systems 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 an LCA for wind turbines. In modeling the lifecycle emissions of wind onshore 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. The climate results will thus be more conservative than would be the case if it was assumed a decreasing average lifecycle emissions value for wind onshore.

The values collected in the RRS model show lifecycle GHG emissions for a range of different wind onshore systems across different regions and system sizes. Table 2.1 presents the boundaries of the data collected on the RRS model and the selected model input for scenario analysis.

Table . Climate Inputs

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Indirect CO2 Emissions (Solution) | *t CO2-eq/TWh* | 20,000 – 43,918 | 22,467 | 30 | 8 |

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[[3]](#footnote-3).

### Financial Inputs

RRS model constructs PDS adoption scenarios for wind onshore generation globally and regionally for each year until 2050. It is modeled both the capital costs and the fixed and variable OM costs associated with the alternative scenarios compared to those of the PD REF scenario. A 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 onshore electricity generation, along with first costs (per functional unit), were calculated.

For the solution (wind onshore), 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 among world regions. The financial inputs used in the model consider an average installation cost of US$1,854 per kilowatt with a learning rate of 14.48. percent, resulting in first costs of US$1,324 per kilowatt in 2030 and US$1,086 in 2050. Variable operation and maintenance costs of US$0.022 per kilowatt-hour, and of US$37.0 per kilowatt for fixed costs are considered for onshore wind, compared to US$0.004 per kilowatt-hour and US$32.95 per kilowatt for the conventional technologies (Tables 2.2. and 2.3). Data points collected that depict costs before 2015 were excluded from the analysis to better account for recent cost reduction trends. In some world regions, reports for first costs have been significantly lower (around US$1,100 per kilowatt e.g. in the United States and China). Nonetheless, because of the differences in levels and speed of adoption at regional scales, more conservative values were chosen.

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 follow a literature review data meta-analysis, and used across all Drawdown electricity generation solutions with this level of agency. 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* | 1,296 – 1,975 | 1,854 | 70 | 14 |
| Fixed Operation and Maintenance Costs (Solution) | *US$2014/kW* | 32.05 – 65.30 | 48.67 | 13 | 5 |
| Variable Operation and Maintenance Costs (Conventional) | *US$2014/kWh* | 0.011 – 0.037 | 0.024 | 29 | 8 |
| Learning Rate Factor (Solution) | % |  | 14.48% | 20 | 8 |

### Technical Inputs

In order to characterize wind onshore technologies compared to conventional technologies, several technical inputs are considered in the RRS as capacity factors and lifetime (Table 2.4 and 2.5). An average capacity factor of 33.6 percent is used for onshore wind turbines, compared to 56.5 percent for conventional technologies (*i.e.* coal, natural gas, and oil power plants).

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* | 55,102 – 81,687 | 68,394 | 11 | 9 |
| Average Annual Use (Solution) | *hours* | 2,247 – 3,641 | 2,944 | 44 | 8 |

## 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.

## 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 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

More research and modeling will be necessary to help policy-makers and project developers understand in detail the benefits of adoption on a more resolute scale, as wind onshore will not always make economic sense nor fit perfectly into any country’s future electricity generation portfolio. In particular, our model holds a number of factors constant in order to keep global-scale modeling from becoming too complex, but it is acknowledged that many of these factors, including prices of fuel and operating costs for conventional electricity, could change considerably over the period of analysis.

The model inputs considered might provide a rather coarse estimate of growth and technology performance and costs on a regional basis and could certainly be improved by the inclusion of specific datasets correlating to the country or region levels. Because of this limitation, it is selected on most cases select a conservative estimate for the climate and financial inputs in the model in order not to overstate the potential benefits of adoption.

# Results

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

## Adoption

Comparing the results from the three modeled scenarios to the Reference Scenario allow estimating the climate and financial impacts of increased adoption of wind systems. The Plausible Scenario (PDS1) projects 17.8 percent of total electricity generation worldwide coming from utility-scale wind onshore technologies by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3), the market share of wind onshore reaches 26.4% on both. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percent.

Much of the onshore growth is projected to continue to take place in OECD nations and Asia. Africa and Latin America are also projected to steadily increase their use of wind power. China already outpaces the growth of Europe but in the next 10 years, the generation in the USA will also be higher than in Europe. Around 2040, India will overcome EU electricity generation coming from onshore wind. Figure 3.1 depicts the long-term pathway trajectories for the different scenarios of wind farms (i.e. onshore).

Table . World Adoption of the Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| **Plausible** | **Drawdown** | **Optimum** |
| Wind Onshore | *Electricity Generation (TWh)* | 689 | 9,052 | 19,092 | 19,092 |
| *(% market)* | 3.06% | 19.8% | 26.9% | 26.9% |

Figure 3.1 World Annual Adoption 2015-2060

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore it is overlaid in the figure.

## 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).

The *Plausible* Scenario results in the avoidance of 50.9 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. Both the *Drawdown* and *Optimum* Scenarios are more ambitious in the growth of wind onshore systems, with impacts on greenhouse gas emissions reductions over 2020-2050 of 152.2 gigatons of carbon dioxide-equivalent. Tables 3.2 and 3.3. provide additional information on the climate impacts of the solution adoption. These reduced emissions would help to avoid costs related to climate change damages, improved public health, air quality, and water consumption.

Table . Climate Impacts

|  |  |  |  |
| --- | --- | --- | --- |
| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **Emissions Reduction in 2050** |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | *(Gt CO2-eq/year)* |
| ***Plausible*** | 3.20 | 50.9 | 3.20 |
| ***Drawdown*** | 8.06 | 152.2 | 8.06 |
| ***Optimum*** | 8.06 | 152.2 | 8.06 |

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the individual 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 48.7 gigatons of carbon dioxide-equivalent in the *Plausible* scenario, 148.2 gigatons of carbon dioxide-equivalent for the *Drawdown* Scenario and 147.1 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** | 4.30 | 0.25 |
| **Drawdown** | 12.69 | 0.60 |
| **Optimum** | 12.69 | 0.60 |

Figure . World AnnualGreenhouse Gas Emissions Reduction 2015-2060

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore the world annual greenhouse gas emission reduction impact it is overlaid in the figure.

## Financial Impacts

The results of the *Plausible* Scenario (PDS1) show that the marginal first costs compared to the *Reference* Scenario would be US$842.9 billion from 2020-50, with nearly US$2.05 trillion in net operating savings over the same period. Increasing the use of onshore wind from 5.09 percent in 2014 to 17.83 percent of world electricity generation by 2050 would require an estimated US$4.49 trillion in cumulative first costs.

Both PDS2 and PDS3 have similar numbers with near US$1.66 trillion of marginal first costs and over 6 trillion of net operating cost savings. Below in table 3.4 are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary (Section 6).

Table . Financial Impacts

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Operating Savings** | **Lifetime Cashflow Savings NPV (of All Implementation Units)** |
| *2015-2050 Billion USD* | *2015-2050 Billion USD* | *2020-2050 Billion USD* | *Billion USD* |
| **Plausible** | 5,821 | 843 | 2,051 | 137 |
| **Drawdown** | 8,865 | 1,658 | 6,108 | 560 |
| **Optimum** | 8,865 | 1,658 | 6,116 | 561 |

Figure .3 World Operating Costs Reduction 2015-2060

# Discussion

Wind power plays a large and essential role in any long-term projections toward a low-carbon future: wind has large megawatt capability, is globally available, and the output of wind and solar is complementary in many regions of the world. 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.

Project Drawdown models three scenarios, where one (i.e. Plausible), is an optimistic but plausible scenario where wind power provides almost a quarter of world electricity generation by 2050. As abovementioned, this scenario could significantly reduce future GHG emissions and help drawdown the amount of carbon in the atmosphere by more than 7 ppm by 2050. These could be seen as 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.

The other two Drawdown scenarios are more ambitious, with significantly higher emissions reduction. Though, coupled with solar technologies, wind is probably the most shelf-ready technology available today to radically transform the global electricity generation system to one that does not emit carbon into the atmosphere.

One of the most important determinants of future wind technologies use will be its cost. After a brief increase, the LCOE of wind has again been on the decline and competitive with new fossil fuel plants in several countries. It is also expected a sharp declining of first costs as the size of the turbines and the number of projects increase. Financial and regulatory stability could help ensure that 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 limit or price the external costs of fossil fuels.

Onshore wind farms have small footprints, typically using no more than 1 percent of the land they sit on, so grazing, farming, recreation, or conservation can happen simultaneously with power generation. What’s more, it takes one year or less to build a wind farm—quickly producing energy and a return on investment.

Notwithstanding its local impacts, using wind power to offset fossil generation brings potential public health and environmental benefits, especially in the form of reduced air pollution since wind power produces no direct air emissions and have very low lifecycle emissions.

## Limitations

The accelerated installation of new wind capacity will not be without challenges, however, as traditional electricity markets and grids are in many cases not primed for a high penetration of intermittent, renewable energy. Wind speeds vary on a seasonal and hourly basis, requiring backup power or storage at certain times to meet electricity demand. The increased use of wind and solar may require investments and improvements in grid infrastructure and the flexibility of power systems. 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.

The variable nature of wind means there are times when turbines are not turning. Wind energy, like other sources of energy, is part of a system. Investment in 24-7 renewables such as geothermal, energy storage, transmission infrastructure, and distributed generation is essential to its growth.

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 ETP (2016 and 2017) and Greenpeace (2015). The results of the *Plausible* Scenario are higher than those of the 2°C Scenario of IEA ETP (2017), which estimates the growth of onshore wind to reach only 14.5 percent of the market in 2050. This is, in part, a result of the significant proportion of coal and natural gas power plants with carbon capture and storage projected by the IEA, which is not considered in this analysis and a different level of the global electricity generation. Compared to the Greenpeace Energy [R]evolution Scenario (Greenpeace, 2015), the results are higher for electricity generated but lower on market share (Table 4.1).

Table . Benchmarks

|  |  |  |
| --- | --- | --- |
| **Source and Scenario** | **Electricity Generation in 2050 (TWh)** | **Market Share in 2050 (%)** |
| **Project Drawdown – Plausible Scenario (PDS1)** | **9,052** | **19.8%** |
| **Project Drawdown – Drawdown Scenario (PDS2)** | **19,092** | **26.9%** |
| **Project Drawdown – Optimum Scenario (PDS3)** | **19,092** | **26.9%** |
| IEA Energy Technologies Perspectives (2016) – 6DS | 3,761 | 7.3% |
| IEA Energy Technologies Perspectives (2016) – 4DS | 4,743 | 10.1% |
| IEA Energy Technologies Perspectives (2016) – 2DS | 6,011 | 14.5% |
| Greenpeace Energy [R]evolution (2015) – Reference Scenario | 2,681 | 5.4% |
| Greenpeace Energy [R]evolution (2015) – Energy Revolution Scenario | 10,930 | 21.9% |
| Greenpeace Energy [R]evolution (2015) – Advanced Energy Revolution Scenario | 15,343 | 22.7% |
| IEA Energy Technologies Perspectives (2017) – Reference Technology Scenario | 4,678 | 10.0% |
| IEA Energy Technologies Perspectives (2017) – 2DS | 6,486 | 15.2% |
| IEA Energy Technologies Perspectives (2017) – B2DS | 6,851 | 15.5% |

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# 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 considers, 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 drop 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. Only Arent *et al.* include biomass as renewable energy. [↑](#footnote-ref-1)
2. 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-2)
3. 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-3)