**Technical assessment for**

**Micro Wind Turbines**

Sector: Electricity generation

Agency Level: Households and Commercial

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

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# Acronyms and Symbols

* CF – Capacity Factor
* DOE – Department of Energy (US).
* EIA - U.S. Energy Information Administration
* ETP – Energy Technology Perspectives
* EWEA – European Wind Energy Association
* EWG – Energy Watch Group
* GBP – Great Britain Pounds
* GHG – Greenhouse Gases Emissions
* GW - Gigawatts
* HAWT – Horizontal Axis Wind Turbines
* IEA - International Energy Agency’s
* LCA – Life Cycle Assessment
* LUT – Lappeenranta University of Technology
* M-HAWT – Micro-Horizontal Axis Wind Turbine
* M-VAWT – Micro-Vertical Axis Wind Turbine
* MW – Megawatt
* MWT – Micro Wind Turbines
* NREL - National Renewable Energy Laboratory
* O&M - Operation and Maintenance
* PDS – Project Drawdown Scenario
* PV – Photovoltaic
* RRS – Project Drawdown Reduction and Replacement Solutions Model
* SWWR – Small Wind World Report
* TAM - Total Addressable Market
* TWh - Terawatt-Hours
* UK – United Kingdom
* US – United States
* VAWT – Vertical Axis Wind Turbines
* WEO – World Energy Outlook
* WWEA – World Wind Energy Association

# Executive Summary

Project Drawdown defines *micro wind* as: electricity-generating wind turbines with capacity of 100 kilowatts or less. This solution replaces conventional electricity-generating technologies such as coal, oil, and natural gas power plants. In recent years, attention has been given to large utility-scale wind turbines, though the *micro wind* market offers individuals a good opportunity to become more self-reliant and less dependent on the grid to serve their electricity needs. Small wind turbines remain more expensive than large turbines, especially if the objective is to produce electricity for the grid, since the electrical connection and maintenance are a much higher proportion of the capital value of a distributed system. However, small wind turbines can be integrated into urban infrastructure, such as building-mounted micro turbines. The micro turbine market has been growing steadily over the past few years. Though it has thus far been concentrated mostly in the United States, China, the United Kingdom, and Germany, the increasing electrification of the developing world offers the industry phenomenal inroads for further expansion and development.

This analysis models any wind turbine that is rated less than or equal to 100 kilowatts. The total addressable market for micro wind is based on projected global electricity generation in terawatt-hours from 2020-2050, with current adoption in 2018 estimated from installed capacity figures at 0.0097 percent (2.18 terawatt-hours) of global generation or TAM – total addressable market.

Impacts of increased adoption of *micro wind* from 2020-2050 were generated based on three growth scenarios derived from the evaluation of scenarios from global energy systems models. These three scenarios were assessed in comparison to a *Reference*Scenario where the solution’s market share was fixed at the current levels of 2018. The *Plausible* Scenario This scenario follows ambitious adoption trajectories of onshore wind adoption from IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Grantham Institute and Carbon Tracker (2017) Strong climate mitigation policies with lower costs for solar photovoltaics and electric vehicles scenario using a medium growth trajectory. *Micro wind’s* current share (0.22 percent) of total onshore wind is assumed to grow in parallel, capturing 0.04 percent of the market share in 2050. *The Drawdown* Scenario follows a high growth trend derived from the same abovementioned scenarios estimated yearly adoption, representing 0.035 percent of the electricity generation mix in 2050. The *Optimum* Scenario is based on the 100% RES scenarios of electricity generation by 2050 of Ram *et al.* (2019) portraying a 0.08% of the electricity generation mix in 2050 with 59.7TWh.

The results for the *Plausible* Scenario show that the marginal first cost compared to the *Reference* Scenario would be US$54.1 billion from 2020-50, with approximately -US$11.6 billion in savings from *micro wind* over the same period. Increasing the use of *micro wind* from 0.007 percent in 2014 to 0.035 percent of world electricity generation by 2050 would require an estimated US$80.1 billion in cumulative first costs. Under the *Plausible* Scenario, this solution has a limited contribution to avoided emissions during 2020-2050 of just 0.10 gigatons of carbon dioxide-equivalent. *Drawdown* and *Optimum* Scenarios have slightly higher impacts on greenhouse gas emission reductions over 2020-2050 of 0.13 and 0.29 gigatons, respectively.

Because micro wind turbines are such an emerging technology, there is a lot of uncertainty around how the technology will grow. Advancements in the lifetimes of micro turbines are the type of benefit that take decades to creep into the marketplace. As such, their impact may not be felt until midway through the 21st century. The potential of building-integrated micro wind turbines is increasingly being explored to generate clean energy on-site. However, at the moment, uncertainty about how factors such as low wind speeds, high levels of turbulence, noise, visual impact, and animal strikes influence the performance of micro wind turbines make it hard to determine their true potential in this form.

# Literature Review

## 1.1 State of Micro Wind Turbines technology

Wind or moving air is caused by difference in air pressure within our atmosphere. These differences in pressure in our atmosphere are created by the sun unevenly heating the surface of the earth creating hot and cold spots. Warm air rises, creating a low pressure zone near the surface. Colder, denser air near the surface in a high pressure zone, flows in to take its place. This flow is called ‘wind’ (DOE, 2008).

Humans have been harnessing the power in the wind since early recorded history. As early as 5000 B.C., wind was used to propel boats along the Nile River. Between 500 and 900 B.C., the Persians used wind power to pump water and grid grain. Eventually around 1000 A.D. wind power technology spread north to European countries such as the Netherlands which adapted windmills to help drain lakes and marshes.  The close of the 19th century ushered in a new era of electrification. But it was not until the late 20th century that older technologies, like windmills, were adopted for generating electricity (Wiser, 2011).

Wind turbines convert the kinetic energy in the wind to mechanical energy which is eventually converted to electricity. The blades of modern wind turbines are modeled after airplane wings. As air moves past the blades, lift is generated. In the context of wind turbines, the lift results in rotational motion. This mechanical motion is converted to electricity by a series of gears and power converters. Newer turbines, with state-of-the-art conversion electronics, are able to bypass the need for gearboxes, altogether (DOE, ND).

Three different wind speeds characterize the performance of wind turbines: cut in speed, rated speed and cut out speed. These metrics are typically plotted on a power curve, an example of which can be seen in Figure 1.1.

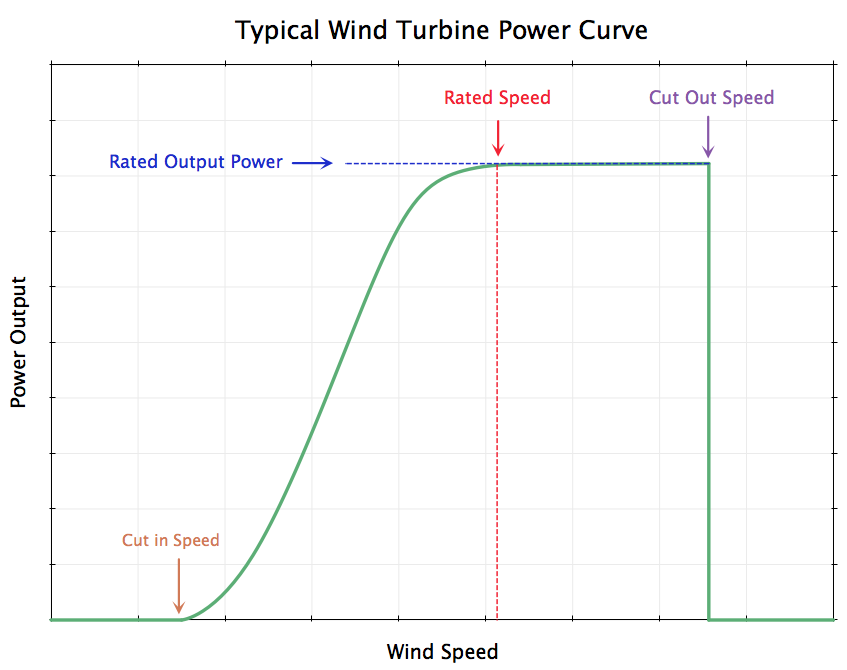
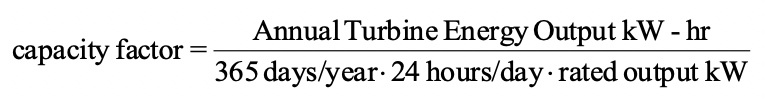


Figure .1 Typical Wind Turbine Power Curve

The cut in wind speed is the speed at which the turbine starts to convert the power in the wind to mechanical power—i.e. “starts working.” The rated speed is the speed at which the maximum power output of the turbine is achieved. The cut out wind speed is the speed at which the turbine can no longer function: For safety and engineering reasons, wind turbines don’t operate when the winds are higher than a certain level. To prevent damage during abnormally high wind events (e.g. hurricanes, tornadoes or strong thunderstorms) turbines ceases to operate (Zayas *et al*., 2015).

Wind energy available for conversion depends on the wind speed and the swept area of the turbine. The output power from a wind turbine is proportional to the kinetic energy (0.5ρv3) present in the wind that impinges on the turbine blades, and is thus proportional to the cube of the average wind speed. For the purposes of this analysis, it’s necessary to define capacity factor: a quantity describing how efficiently wind turbines extract power from the wind. The underlying laws of physics dictate that the maximum capacity factor for any wind turbine is the Betz limit: 0.59. The betz limit dictates the maximum fraction of. kinetic energy that can be extracted from a moving fluid under free stream conditions where is the capacity factor as commonly defined is a ratio of generation actual generation to the potential generation based upon continuous operation at rated power. Therefore the bezs limit is an instantaneous value and our limits to efficiency not the capacity factor. Equation 1 provides an easy estimate for calculating capacity factor (CF):

 Eq. 1

Note that annual turbine energy output is sensitive to the annual average wind speed: the higher the wind speed, the higher the annual energy output. Doubly so, considering the cubic relationship between wind speed and power. For reference, real world capacity factors range from 25% to 50%.

Wind turbines come in a variety of sizes. Large, utility scale turbines are able to generate upwards of 5 MW and are typically installed in a group, a so-called “wind farm.” Micro wind turbines are more akin to windmills of old: only one is installed at a particular location. In fact, until about the 1980s when interest in megawatt-size turbines piqued, all wind energy was considered “micro.” (WWEA, 2015).

The exponential growth of turbine size was driven by economies of scale. Small wind turbines remain still more expensive than large ones, especially if the objective is to produce electricity for the grid (the cost of turbines of size < 2.5 kW is ~$ 8000/kW, while that of utility scale wind turbines can go as low as $ 5000/kW) Sources say that this is because the controls, electrical connection to the grid and maintenance are a much higher proportion of the capital value of the system. However, small wind turbines can be integrated into urban infrastructure such as buildings mounted MWTs, while larger turbines cannot. They thus have modularity advantages. In addition, no further infrastructure is required to connect MWTs unlike in the case of large scaled commercial wind turbines.

Frustratingly, there is no universal definition of small/micro wind turbines. Some organizations explicitly differentiate between micro and small, citing specific generating capacities for each category. For example, the International Energy Agency (IEA) defines micro wind as any turbine with a swept area smaller than 200 m2 and a capacity under 50 kW. Alternatively, the American Wind Energy Association specifies small wind as any turbine with a capacity of less than 100 kW. Others combine everything that’s not part of a utility scale wind farm under the label of “small.” Figure 1.2 describes how various wind energy associations define “micro wind.” (WWEA, 2015).

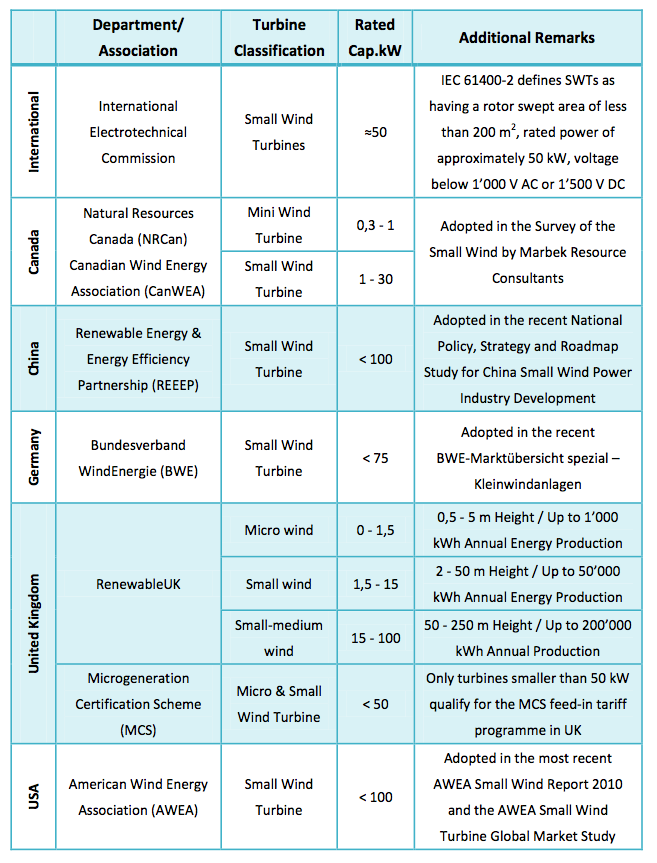


Figure 1.2 Turbine sizes and classifications (Source: adapted from 2015 World Wind Market Report)

For the purposes of this analysis, wind turbines that have a capacity of 100 kW or less will be defined as a micro wind turbine (MWT). This is because it encapsulates all the above definitions of micro and small turbines. The Project Drawdown ‘Wind Solution’ examines the effect of all wind turbines greater than 100 kW. To further help understand the scales at which MWTs operate, Figure 1.3 illustrates the size discrepancy between utility scale wind turbines and MWTs.

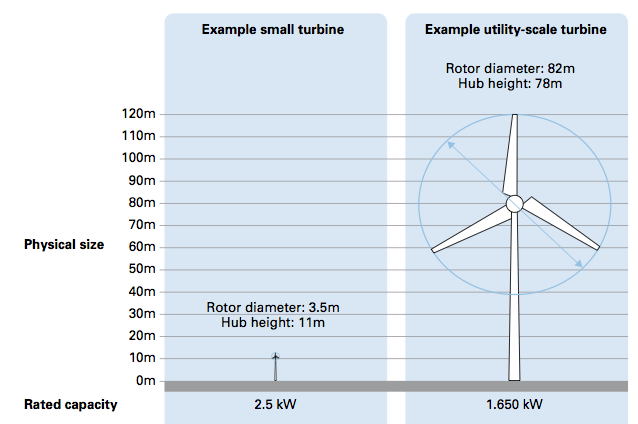


Figure 1.3 Micro Wind Turbine vs Utility Turbine Sizes (Source: Carbon Trust, 2008)

Note: The utility scale turbine is rated 1,650 kW or 1.7 MW

Their comparatively small stature greatly affects the capacity of MWTs: a hub height difference of 67m correlates to 3 orders of magnitude of capacity: 2.4 kW vs 1,650 kW. These differences are important to understand when discussing the results of the study: MWTs have a far smaller impact than their larger, utility scale counterparts.

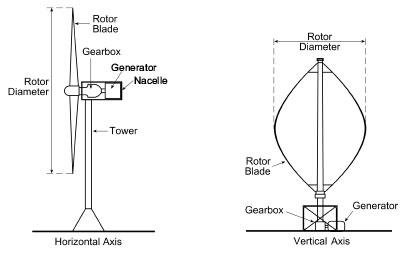
MWTs are either used in a distributed generation scenario, where the electricity generated interacts with the grid, or in stand-alone or “off-grid” applications. Paralleling the history of windmills, MWTs were originally installed in rural areas to help with water pumping and farming applications. Typically installed in conjunction with a generator, these off-grid hybrid systems still play a major role in the MWT market. Upwards of 80% of MWT manufacturers sell stand-alone systems and in China alone, 97% of MWT sold were for off-grid purposes in 2009 (WWEA, 2014, 2016). Indeed, the growing electrification of China (and the rest of the world, for that matter) will be a boon to the MWT market. Other off-grid MWT applications include powering road signs, security cameras in streets, and navigation beacons and on yachts. On-grid applications have seen a growing demand in developed markets too, especially in the US, UK and Denmark (WWEA, 2014).

Building integrated MWTs is another form that is currently being explored to generate energy on-site. Although there have been successful demonstrations of such MWTs (Ragheb, 2014), at the moment the up-take of MWTs in high density suburban sites is still very small. Uncertainty around the effect of factors such as low wind speeds, high turbulence, noise, visual impact, animal strikes (Peacock et al., 2008) make it difficult to determine the feasibility, efficiency and safety of the deployment of these systems. Makkawi *et al.* (2009) and Ledo *et al.* (2011) further note that at the present moment small wind manufacturers have not fabricated MWTs that operate under low wind speeds, high turbulence and this may explain the modest growth of building mounted wind turbines.

There are two types of MWTs: micro horizontal axis wind turbines (mHAWTs) and micro vertical axis wind turbines (mVAWTs).

1. Micro-HAWTs are essentially miniature versions of utility scale three bladed turbines and having rotor axis parallel to the ground. Unlike VAWT, HAWT has the inertia to start operating by itself, and to automatically yaw and position the turbine blades at the correct angle of attack to the incoming wind at all times (Tummala et al., 2016). The earlier HAWT has dominated the MWT for over 30 years. Owing to high dependence on wind direction, HAWT requires positioning at greater heights where wind condition is consistent. HAWT is best suited to large-scale power generation, greater heights, and at a site with less turbulent wind.
2. Micro-VAWTs are relatively new and have varying shapes and designs with the rotor axis perpendicular to the ground. Because VAWT is able to capture wind flowing in all directions, it is best suited to urban areas and could still generate power even at a shorter height, making it easier to maintain and/or decommissioned. Unlike in HAWT, VAWT do not need self-starting and/or yaw mechanisms. VAWT are in two categories (Tummala et al., 2016):
3. **Darrieus wind turbine** – characterized by straight or curved blades anchored on a vertical hub, and usually driven by the lift forces of the rotating blades;
4. **Savonius wind turbine** – characterized by S-shaped cross-section visible from top view, and it is driven by differential drag forces that help the turbine to spin. Because it is drag drive, it has lower efficiency when compared to other counterparts.

A survey done in 2011 indicated that of a sample set of 327 small wind manufacturers, 74% had invested in mHAWTs, while only 18% had adopted mVAWTs (WWEA, 2016)[[1]](#footnote-1). The primary advantage of mVAWTs is that they are able to capture winds from any direction. MWTs are installed mostly in wind regimes close to the ground, or in turbulent urban environments. The added benefit of a MWT being omnidirectional may prove critical. But since this technology is still so young and untested, additional information is need to prove the validity of the mVAWT industry’s claims (Figure 1.4).

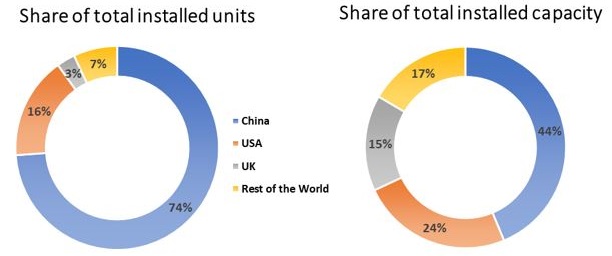


*Figure 1.4 The left figure shows mHAWT . The figure on the right depicts a Darrieus-type mVAWT (Source: Spence, 2012)*

## 1.2 Adoption Path

### 1.2.1 Current Adoption

Th current adoption of micro wind turbines, estimated from installed capacity figures at 0.007 percent (1.72 terawatt-hours) of global generation (WWEA, 2016). MWTs are manufactured primarily in five countries: US, China, UK, Germany and Canada.. In 2017, the majority of MWTs are installed in just four countries: China (44%), US (25%), UK (15%), and Italy (6.3%) (WWEA, 2017). China remains a dominant market and it is home to almost half of the global installed MWT capacity since 2015 to date (WWEA, 2015) (Figure 1.5).



*Figure 1.5 Share of total installed capacity of MWTs (Source: WWEA, 2017)*

In the USA, the Department of Energy (DOE) publishes reports with data about MWT installation in the US. The American Wind Energy Association has set itself a target to install 50,000 MW by 2020 based on the number of houses in the United States connected to the grid with an accompanying 0.5 -1acre or above of land area, commercial properties and public works that could potentially install MWTs (NREL, 2002). The MWT installation in 2014 was however only ~ 226 MW according to WWEA (2016). The current state of unreliability of technology as well as the still open questions about siting therefore make it unlikely that such an ambitious target will be met.

In China, which currently leads in the deployment of MWTs, most MWTs are currently installed by farmers, herdsmen and fishermen who live in areas without electricity according to Zhang and Qi (2011). They see the potential markets for MWTs in the 11.47 million population, at least 40% of which can be electrified using MWTs that still live in areas without electricity. However, it is unclear at the present moment when breakthroughs in the cost of MWTs will occur in order for this technology to be accessible by these markets.

In the UK, the third largest MWT market, the last few years has seen a significant growth in the annual deployment of MWTs in the 1.5-15 kW and the 15-100 kW market segments, and it is expected that the 1.5-15 kW segment will grow once a General Permitted Development Order is introduced for turbines on non-domestic premises (Renewables UK, 2012). However, the uncertainty around such a policy makes it difficult to project the adoption of MWTs in the time frame considered by Project Drawdown.

Based on the 2016 Small Wind World Reports (WWEA, 2016), The Chair of the World Wind Energy Association (WWEA) notes that after 2013, the world wind energy market stabilized with the growth of MWTs in the US at a 1% p.a, while the growth in China was ~10%. He notes that in the UK, however, the growth in MWTs was 19%, after only 2% growth after 2013. He states that a minimum of 11% growth globally is expected to be seen until 2016, after which he predicts a global growth of 20% till 2020.

### 1.2.2 Trends to Accelerate Adoption

Looking at this technology from a policy perspective indicates that the successful global adoption of MWTs will greatly benefit from stable support schemes: feed-in-tariffs, tax credits, capital subsidies, net metering. However, economic subsidies may not work well, compared to production subsidies, as the former tend to incentivize the sale of hardware, thereby missing the energy savings benefits (Windustry, ND). It is to be noted however, that although price support is crucial, it is never a sufficient condition on its own, the Global Wind Policy Review identified (IRENA, 2012) seven criteria as critical for the development of wind energy in addition to economic incentives, such as: expression of political commitment from government, effective rule of law and transparency and an effective administrative and permitting process, a functioning finance sector and clear and effective pricing structures, grid access, etc. (WWEA, 2014).

Owing to the suitability of micro vertical axis wind turbines (mVAWT) for urban environments (Lombardi *et al*., 2018), Mega City policies that support power generation from MWTs will help drive adoption. In addition, other drivers may include corporate sourcing of renewables generated from MWTs.

### 1.2.3 Barriers to Adoption

The key drivers or limitations for widespread adoption of MWTs is cost, and support mechanisms in place. MWTs have a much higher cost per kW, compared to utility scale wind turbines. This is primarily because of volume: wind farms are comprised of hundreds of turbines, whereas MWTs are installed individually, usually only one per site.  These high capital costs are prohibitive to many consumers who may otherwise be eager to install MWTs on their property. In the US turbines less than 2.5 kW cost on average USD 8,200/kW, turbines between 2.5 – 10 kW cost USD 7,200/kW, while projects between 11 – 100 kW cost USD 6,000/kW. To compare this, a commercial wind turbine of size 2 MW, costs roughly between USD 3-4 million, which is - USD 1,500 – 2,000/kW (Orrell et al., 2014). These high capital costs are prohibitive to many consumers who may otherwise be eager to install MWTs.

### 1.2.4 Adoption Potential

As the demand for renewable energy in general increases with total addressable market (TAM), so too will the demand for MWTs. The desire to electrify more areas of the planet will help spur development of MWTs. Some forecasts show that there will be a 19-35% annual increase in MWT installed capacity. Additionally, a compound growth rate of 20% is possible per year between 2015-2020. By 2020, some experts estimate that new installations could top 240 MW per year, resulting in a cumulative installation of 1.75 GW (WWEA, 2014).

Currently market trends are reported to lean towards on-grid MWT systems with larger capacity, however off-grid systems continue to play an important role in developing countries. In China, off-grid MWTs comprised of 97% of the market in 2009, in the US, off-grid small wind turbines comprise of most MWTS deployed in distributed wind applications. In the UK, results from a survey indicate that there are cumulatively more off-grid MWTs than on-grid. This is because of the use of MWTs on yachts. As a result, all off-grid installations in 2013 and 2014 were sub 20 kW. Any turbine larger than this was connected to the grid. The balance has consistently remained at 60% off-grid, 40% on-grid since 2012. In developing countries there is the potential of growth in medium wind off-grid applications due to the increasing difficulty of mains grid connection. Additionally, the increasing uptake of storage mechanisms can provide a viable option for larger-scale off-grid applications (RenewableUK, 2015).

## Advantages and disadvantages of Micro Wind Turbines

### 1.3.1 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 to micro wind turbines the ones that use the same resource (wind energy) for electricity generation or that could be used at a similar agency level such as in off-grid or standalone modes:

* **Wind Onshore:** onshore utility-scale wind power technologies are located within the land boundary of a region, and widely spaced about 4 rotor diameters apart to minimize reduction of power output arising from downwind turbines operating in the wake of upwind turbines. Utility-scale onshore wind provides electricity at the same level of agency as the offshore wind power, relatively easier to build and maintain, but with potentially high visual issues which makes planning permissions and public acceptance more challenging.
* **Wind Offshore:** offshore utility-scale wind power technologies either installed in the bottom of the sea or floating devices.
* **Rooftop Solar Photovoltaic System (SPV):** In fact, the SPV programs started with small scale household and community-based systems and later on grew in scale to utility systems. The underlying technology is the same – the difference being in the scale and the implementing agency (i.e. household or utility). Rooftop and small community SPV programs still account for a roughly estimated 40% of all global investments in SPV and are the favored solution for providing decentralized and off-grid power to remote habitations and households.
* **Micro hydropower (MHP):** Usually, MHP is a type of small hydropower with capacity up to 100 kW (Jawahar & Michael, 2017). Installations below 5 kW are known as the Pico hydropower, and they offer on-site power generation solutions in a way similar to Micro Wind turbines.
* **Household biogas power plant:** Family-sized biogas-powered systems could be a competitive solution relative to Micro Wind. While most household biogas plants are used to meet heating and cooking needs, some are complimented with small biogas-powered electricity generators to convert the biogas into electricity with an estimated ratio of 0.65 cubic meter to 1 kW (Yasar et al., 2017).
* **Micro CHP:** Just like the cogeneration power plants, micro CHP (mCHP) generates both electricity and heat from the same source such as biogas. The output of a micro CHP is usually 6:1, that is 6-part heat and 1-part electricity (EST, 2019). Micro CHP could be free standing or hung on the wall like domestic boilers. However, it is distinguishable from boilers because of its simultaneous generation of heat and electricity. Micro CHP considers three posisbilities (EST, 2019):
  + A relatively new *Stirling engine mCHP*, with heat to electricity output ration of 6:1.
  + The newest and less common *fuel cell CHP*, that operates by chemically taking energy from fuels without the need for combustion.
  + A more matured and common *internal combustion engine CHP*, which is essentially a modified diesel-powered truck engine which runs on lighter fuels such as biogas or natural gas. Heat output is taken from the cooling water coming from the engine, and exhaust system, while electricity is generated by connecting the IC CHP directly to an electrical generator.

### 1.3.2 Arguments for Adoption

Looking thirty years ahead, it is undeniable that more parts of the planet will become electrified, mostly in the developing world (Ranaboldo e*t al*., 2014; Li, 2015). Microgrid technology, including MWTs, offers a quick, easy and relatively inexpensive method of electrifying these regions. Compared to the upfront capital investments of natural gas power plants and a network of transmission lines, MWTs, with robust storage capabilities, are much cheaper, and most of all, cleaner.

In the developed world, MWTs can be seen as a “bonus.” The vast majority of citizens in developed countries will continue to be connected to the electrical grid (Nandi *et al*., 2010). The trends of utility scale renewable energy will continue upwards, driving down the use of carbon-rich sources of electricity. MWTs and other microgrid solutions will enable these citizens to generate spare electricity on site and, depending on their situations, either store it or send it back into the grid via net metering.

Relevant to the current water shortages plaguing many parts of the world, MWTs require no water to generate electricity. The only water required is in the manufacturing process. While reducing GHGs is noble and should remain a top priority, water conservation should nevertheless not be neglected. Indeed an under-touted advantage of MWTs, and wind energy in general, is its minimal use of water. (DOE, 2008).

While many developed countries are adopting utility-scale onshore and offshore wind power to meet their clean energy targets, there are concerns that meeting 10 – 15% of global energy demand with utility-scale wind power plants could lead to land surface temperature rise of 1°C (Tummala *et al*., 2016).

### 1.3.3 Additional Benefits and Burdens

Siting is another factor that affects the adoption of MWTs. MWTs are very susceptible to siting conditions. Wind turbines operate best when the wind reaching the turbine blades is not affected by obstacles, since they slow the wind down and increase turbulence- both of which reduce the performance of the wind turbine. Because of their size and generating capacity, MWTs are much more susceptible to siting conditions and typically have low capacity factors. Unfortunately, because this aspect of the MWT industry is still very much in its infancy, there has been little advancement in this area.

Software suites exist for utility scale siting, but such solutions are inappropriate for the scale of MWTs, as these companies have little incentive to invest in residential scale siting solutions. Acquiring such data and developing techniques to improve siting is cost prohibitive — better to stick to crude anemometers and simple data acquisition software. Siting constraints thus provide a bottom-up constraint on the adoption of MWTs. However, as mentioned above understanding these constraints is very much in its infancy. NREL (2007) has issued a ‘Small Wind Electric Systems: A U.S. Consumer Guide that details the following broad guidelines for a small wind energy system to be a practical investment for citizens in the United States at the current time:

* Property has a good wind resource and is in a remote location without easy access to utility lines.
* Home or business is located on at least one acre of land in a rural area.
* Average electricity bills are over $150 per month.
* The investor is comfortable with long term investments.

The criteria that electricity bills > $150/month means that at the moment very few households around the world meet this criterion, even in rich countries. However, in the future, with the falling costs of MWTs, MWTs can become a financially feasible investment for more households.

Continued popularity of distributed generation/microgrids will only further benefit the MWT industry. Skyscrapers and other large complexes behave like mini cities. It is a natural fit, then, to incorporate MWTs into these systems. Relatedly, skyscrapers have the added benefit of easy access to high wind regimes. A characteristic of the atmosphere is that wind speeds increase with height. Hence the push by utility scale wind developers for higher wind turbines. In fact, it is been quipped that wind power is viable anywhere on the planet, so long as the turbine is high enough. Installing MWTs atop skyscrapers places them directly in high wind regimes, without the burden and cost of cumbersome towers (Lazard, 2014).

But where MWTs have the biggest potential to shine is incorporation with other energy sources. Because of the variability of the wind, MWTs cannot generate electricity at all times. To solve this problem, MWTs are typically installed in conjunction with diesel generators (Alliance for Rural Electrification, 2012). According to some in the industry, this is one aspect ripe for improvement (IRENA, 2012). Balancing low carbon emitting wind turbines with high carbon diesel acts to “cancel out” the environmental benefits of MWTs. One solution is to pair solar PV systems with MWTs and there are already some systems on the market that marry these two technologies (Attaianese *et al.*, 2014). Another solution would be replacement of the diesel generators altogether. In the next 18 months, Tesla will be introducing a residential battery storage unit. Paring such devices with MWTs would enable storage of unused electricity. This has the potential to be a “game changer” not just for the MWT market, but for all small scale renewable systems plagued by variability of the resource. Table 1.1 presents a comparison of selected pros and cons of the solution with others either in the same sector, same level of agency and/or with the same energy source.

Table .1 Micro wind solution compared to other similar alternatives sand to conventional electricity generation technologies

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

# Methodology

## 2.1 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 emissions reduction and financial impacts of increased adoption of micro wind turbines (MWT). The model used for this analysis constructs both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for MWT. 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 MWT remains fixed at the current base-year (i.e. 2014) percentage of Total Addressable Market (TAM), estimated from installed capacity figures at 0.0010 percent (2.18 terawatt-hours) of global generation. 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 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 MWT, as well as the contribution this adoption can make to annual and cumulative emissions reduction.

## Data Sources

This section presents key data sources utilized in the model to evaluate the adoption of micro wind turbines. 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, eight data points reported in the literature and in some cases as many as 18. This allows to calculate robust and reliable inputs for the financial, technological and climate analyses that represent both optimistic and conservative estimates for the future costs and benefits of adopting this solution.

In terms of adoption, 2017 RRS model version included 15 scenarios from sources including WWEA (2016), IEA ETP (2016), Greenpeace (2015), AMPERE (2014). Updasted 2019 adoptions were indirectly calculated from several scenarios of onshore wind adoption in various sources including IEA WEO (2018b), IEA ETP (2017), Grantham (2017), IEEJ (2019), Equinor (2018), and Ram et al. (2017).

On the capital or first costs, IRENA (2016) presents a global average low and high ranges of below 100 kW MWT as 6,000 – 8,670 $2014/kW; US DOE (2017) presents 9,771 $2014/kW for 10 – 20 kW MWT installed in 2017; and Grieser *et al.* (2015) presents in $2014:

* $5,543/kW for 2.4 kW HAWT Skystr system (3 – 10 m/s),
* $15,863/kW for 6.5 kW HAWT Aventa system (2 – 6 m/s), and
* $7,206/kW for 3 kW VAWT Envento system (3 – 14 m/s)

In China, the capital cost is cheaper than the global average at $1,995/kW in 2014 USD. These trends show that the installed cost of MWT depends on regions, turbine make, range of operational wind speed, turbine capacity, and the axis of rotation. A VAWT system is slightly more expensive than the same size of horizontal axis counterpart.

Cost estimates for fixed operation and maintenance (OM) of micro wind systems are limited and were collected from *e.g.* Orrell *at al.* (2013); Global CCS Institute (ND). These estimates were used to calculate total operating costs of micro wind technologies adoption, which, combined with capital costs for installation, represent the total financial costs of adopting this solution in the PDS scenario. Fixed operation and maintenance costs for both renewable and conventional generation technologies can include expenses such as day-to-day preventative and corrective maintenance, labor costs, asset and site management, and maintaining health and safety, among others (Lo, 2014). Average fuel price was calculated considering average prices for both coal, oil and natural gas from 2005-2014 using IEA data (IEA, 2016a).

In order to compare capital and OM costs of micro wind installation in the PDS scenarios to that of conventional generation technologies, it was obtained cost data for fossil fuel-based electricity generating sources from the IPCC 5th Assessment Report (IPCC, 2014) which conducted its own sensitivity analysis of a number of sources from the literature[[2]](#footnote-2), and other sources such as OECD (2015), Lazard (2016). In all variables for conventional electricity generation sources, data for coal, oil and natural gas (primarily pulverized coal and combined cycle gas turbine technologies) were included and a weighted average. The weights are based on the percentage, for each fuel on the total global electricity generation for 2018.

In order to calculate the total impacts and benefits of increased solution adoption (on PDS scenarios), technical data was also integrated, including average annual use, plants lifetime, and average efficiencies. All three of these are key to determining the variable OM costs and the total fuel costs for conventional generation sources, as these costs are determined by the average number of hours the power plant is generating electricity, as well as the average price of fuel inputs and the average efficiency. Average plants efficiency is calculated from several global sources (IPCC, 2014; IEA, 2010), as well as from the U.S. EIA (2015).

The Low Carbon trust (2008) states that anecdotal evidence suggests that the capacity factors of small wind turbines ranges from 15-20%. The UK- Small Wind Survey-2008 (AEA, 2009) indicates that capacity factors range from 0.1 for turbines of the size 0 to 1.5kW, to 0.17 for turbines from 1.5 kW to 50 kW. The 2015 Distributed Wind Market report shows the capacity factors of wind turbines as a function of turbine rating in the US for 2013 and 2014. Capacity factors range from < 10% for turbines < 10 kW to >40% for larger turbines. Datasheets from manufacturers provided in the report indicate that commercial MWTs have capacity factors ranging between 0.15-0.20. Caveat: The estimates below are not representative of all the micro turbines on the market. In addition, the wind turbines represented below have power ratings <11 kW, while the section of micro wind turbines we are looking at span 1-100kW.MWTs last between 20-30 years. Most manufacturers (EWEA, 2016) have stated that the design life time is 20 years. Lenzen *et al.* (2012) provides a table containing the lifetimes of different commercially manufactured MWTs in different parts of the world ranging from 20-30 years.

The model’s analysis of the climate impacts of adoption are primarily derived from the direct emissions factor associated with the replacement of conventional generating technologies with micro wind. This methodology is explained in greater detail in Drawdown RRS model framework and guidelines. In order to account for indirect emissions from conventional technologies and MWT systems—primarily those lifecycle emissions associated with manufacturing, transporting, installing and other non-generation activities—it were analyzed a range of peer-reviewed lifecycle analysis (LCA) studies for different types of MWT technologies available in the market. The analysis draws from information reported in e.g. NTEL (2013), Masanet *et al.* (2013); Nugent and Sovacool (2014) and Gusano (2016). For example, Nugent and Sovaccol (2014) state that MWT carbon emissions range from 17.8 g CO2eq/kWh to 364 g CO2eq/kWh (depending on the type of system installed). Because the technology is so young and with low maturity levels, MWT improvements are difficult to accurately assess, so learning rate data sources followed the ones used in the wind onshore solution (e.g. Rubin *et al.*, 2015; Hayward and Graham; 2013, Wiser; 2016, Tsiropoulos *et al*.; 2018).

## Total Addressable Market

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

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

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

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

## Adoption Scenarios

Because MWT solution has low levels of electricity generation worldwide, future projections over the next 30 years might encompass significant challenges and assumptions. Also, limited availability of adoption data means high degree of uncertainties in future adoption trajectories. Alternative adoption scenarios included in the RRS model are based on two approaches: (i) the future projections of utility scale onshore wind applying the current share of micro wind to model several alternative adoptions; (ii) future adoption trajectories that follow the cumulative annual growth rate (CAGR) for low, medium, and high scenarios determined from the historical adoptions of MWT.

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

### Reference Case / Current Adoption

For the Reference (REF), adoption is fixed at the current adoption[[3]](#footnote-3) (in percent) of the market. That is, the current percentage of total electricity generation (TWh) estimated to result from micro wind turbines constant throughout the study period to 2050. As the market grows, the total number of micro wind systems adopted grows equally to maintain the percent adoption at its current 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, to compare the impact of an increased adoption of the solution to a reference case scenario, being:

#### Plausible Scenario

This scenario represents an incremental and plausible growth of renewable energy solutions using medium to high growth trajectories to 2050 depending on the current maturity levels of the technology, and bounded by existing ambitious projections from other global energy systems models. For micro wind turbines, this scenario is based on the evaluation of yearly averages of four ambitious scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Grantham Institute and Carbon Tracker (2017) Strong climate mitigation policies with Lower costs for solar PV and EV scenario using a medium growth trajectory. *Micro wind’s* current share (0.22 percent) of total onshore wind is assumed to grow in parallel, capturing 0.04 percent of the market share in 2050.

#### Drawdown 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 micro wind turbines, this scenario is based on the same adoption scenarios as the Plausible scenario, with an evaluation of yearly averages of four optimistic scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Grantham Institute and Carbon Tracker (2017) Strong. climate mitigation policies with Lower costs for solar PV and EV scenario using a high growth trajectory.

#### Optimum Scenario

This scenario represents the most optimistic case, in which clean, renewable energy solutions such as wind, solar, and other renewable energy sources capture 100% of electricity generation by 2050, with both fossil fuels and transitional solutions fully phasing out by 2050. This scenario for micro wind turbines is based on the 100% RES scenarios of electricity generation by 2050 of Ram et al. (2019).

## Inputs

### 2.5.1 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 micro wind turbines 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, micro wind turbines 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 micro wind systems. In modeling the lifecycle emissions of MWT in the scenarios, it is used a fixed value (t CO2-eq per TWh) considering information from several onshore wind technologies 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 MWT systems. Table 2.1 presents the boundaries of the data boundaries on the model and the selected model input.

Table . Climate Inputs

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Indirect CO2 Emissions (Solution) | *t CO2-eq/TWh* | 400 – 172,090 | 71,049 | 21 | 9 |

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

### Financial Inputs

RRS model constructs PDS adoption scenarios for micro wind turbines generation globally and regionally for each year until 2050. It is modelled both the capital costs and the fixed and variable OM costs associated with the alternative scenarios compared to those of the REF scenario. 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 MWT generation, along with first costs (per functional unit), were calculated. A net present value discount rate of 4%, appropriate when applied to investment decisions made at a household level. The household level discount rate is directly related to decision-making at a household level and likely varies greatly across different regions of the world. Taking the numbers found in the literature above comprises a conservative case.

For the solution (MWT), 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.

Fuel prices for conventional technologies are derived from IEA (2019b) 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.

Tables 2.2. and 2.3 depict the financial inputs used in the RRS model calculations for both conventional technologies and micro wind turbines.

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* | 3,238– 9,722 | 6,480 | 24 | 8 |
| Variable Operation and Maintenance Costs (Solution) | *US$2014/kWh* | 0.01-0.05 | 0.03 | 2 | 1 |
| Fixed Operation and Maintenance Costs (Solution) | *US$2014/kW* | 20 – 250.80 | 127.32 | 9 | 4 |
| Learning Rate Factor (Solution) | % | 4.2 – 154.1% | 9.65% | 20 | 8 |

### Technical Inputs

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* | 24,328-35,404 | 29,866 | 7 | 3 |
| Average Annual Use (Solution) | *hours* | 910 – 2,131 | 1,520 | 36 | 9 |

## 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. Several adoption scenarios linked the growth of MWT with utility scale onshore wind. It is true that the MWT industry has size restrictions that the utility wind industry does not have, but MWT uses essentially the same technology as the utility onshore wind industry, but on a much smaller scale.
2. MWT capacity adoption data for 2014-2015 from the Small World Wind Reports (WWEA, 2015, 2016, 2017), while the 2012, 2013, and 2016 capacity adoption data were collected from the records of Statista (2019). It was assumed that the estimated model’s average capacity factor of 17% is constant for all the years, and therefore was used to convert the capacity adoption (kW) to adoption in functional unit (TWh). These estimated (2012 - 2016) were then prognosticated till 2050, and future updates could be made as more historical data becomes available.
3. The climate mitigation potential calculations in the RRS model assumed that the energy generated by MWTs replaced the electricity generated by the grid. It must be stated here that MWTs in many locations are used as stand-alone systems. It is unlikely that the grid will reach all of these locations in the time period that the model considers and therefore MWTs are not a ‘replacement’ for the grid in all regions.

## 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 micro 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 (for example LED lighting and heat pumps) as well as increased electrification from other solutions like electric vehicles and high-speed rail. Grid emissions factors were calculated based on the annual mix of different electricity generating technologies over time. Emissions factors for each technology were determined through a meta-analysis of multiple sources, accounting for direct and indirect emissions.

## Limitations / Further Developments

The RRS 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, and at agency level.

The RRS model adoption scenarios used are also based on a critical assumption about the percentage of micro wind turbine linked to utility scale wind onshore adoption scenarios.

Another critical assumption that is made on the RRS model results is that all micro wind systems replaces electricity from the grid. This needs further refinement but is seen as a conservative approach, as the grid do not reach all places where MWT systems can be deployed within the timeframe considered by the model. Indeed, in some places it replaces energy from diesel generators which means that the GHG savings of micro wind turbines implementation could be even greater than those calculated by the RRS model.

The modeling approach for the MWT does not account for the hybridization of MWT with other energy sources, which is a popular practice in most sites where MWT have been deployed. Apparently, this might be the reason why the power generation from MWT in functional unit is seldom reported, but rather the installed capacity in implementation unit.

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# Results

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

## Adoption

Comparing the results from the three modeled scenarios to the Reference Scenario allow to estimate the climate and financial impacts of increased adoption of micro wind turbines. The Plausible Scenario (PDS1) projects near 19.26 TWh of total electricity generation worldwide coming from MWT by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3), the market share reaches 0.035 percent and 0.084 percent, respectively. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percent. Figure 3.1 depicts the long term pathway trajectories for the different scenarios of micro wind systems.

Table . World Adoption of the Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| **Plausible** | **Drawdown** | **Optimum** |
| Micro Wind Turbines | *Electricity Generation (TWh)* | 1.48 | 19.36 | 25.11 | 59.73 |
| *(% market)* | 0.0066% | 0.042% | 0.035% | 0.084% |

Figure 3.1 World Annual Adoption 2015-2060

## Climate Impacts

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

The *Plausible* Scenario results in the avoidance of just 0.10 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. Both the *Drawdown* and *Optimum* Scenarios are slightly amore mbitious in the growth of distributed micro wind technologies despite the growth of other more significant technologies, with impacts on greenhouse gas emissions reductions over 2020-2050 of 0.14 and 0.34 gigatons of carbon dioxide-equivalent. These estimates were based on a conservative capacity factor. Since wind power is proportional to the cube of the wind speed, higher wind speeds result in much higher power. Doubling the wind speed in this framework would result in an order of magnitude increase in the carbon savings. Tables 3.2 and 3.3. provide additional information on the climate impacts of the solution adoption.

Table . Climate Impacts

|  |  |  |  |
| --- | --- | --- | --- |
| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **Emissions Reduction in 2050** |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | *(Gt CO2-eq/year)* |
| ***Plausible*** | 0.006 | 0.10 | 0.006 |
| ***Drawdown*** | 0.009 | 0.14 | 0.009 |
| ***Optimum*** | 0.024 | 0.34 | 0.024 |

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined). After integration, the impact on emission reduction for this solution is similar, with 0.1 gigatons of carbon dioxide-equivalent in the *Plausible* scenario, 0.13 gigatons of carbon dioxide-equivalent in the *Drawdown* Scenario and 0.97 gigatons of carbon dioxide-equivalent disclosed in the *Optimum* Scenario. Figure 3.2. show the world annual emissions reduction trajectories for the different scenarios for the long term.

Table . Impacts on Atmospheric Concentrations of CO2-eq

|  |  |  |
| --- | --- | --- |
| **Scenario** | **GHG Concentration Change in 2050** | **GHG Concentration Rate of Change in 2050** |
| *PPM CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| ***Plausible*** | 0.009 | 0.0005 |
| ***Drawdown*** | 0.012 | 0.001 |
| ***Optimum*** | 0.029 | 0.002 |

Figure . World AnnualGreenhouse Gas Emissions Reduction

## Financial Impacts

The financial savings incurred by replacing conventional grid electricity sources with micro wind systems is reduced when compared to other renewable energy sources. The *Plausible* scenario presents US$52.84 billion from marginal first costs and negative US$11.57 billions of net operating savings are projected over the same period. PDS2 results show US$69.64 billion from marginal first costs with while PDS3. consider near US$157.83 billions of marginal first costs and -38.65 billions of net operating savings.

The capital costs for PDS adoption of micro wind will require additional investments, as the cumulative capital costs are just over $78.54 billion on the *Plausible* Scenario, $99.39 billion for Drawdown scenario and 199.33 on the more ambitious adoption *Optimum* scenario. The learning rates used in this analysis close to 10% (i.e. 9.65%) lead to a continued decrease in the capital costs of these distributed micro wind systems. 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*** | 80.1 | 54.1 | -11.56 | -29.14 |
| ***Drawdown*** | 101.3 | 71.2 | -15.57 | -38.11 |
| ***Optimum*** | 203.2 | 161.4 | -38.63 | -86.71 |

Figure .3 World Operating Cost Reduction

# Discussion

## Limitations

MWTs are very much still a nascent technology in many ways. To grow, the industry has to deal with the current high cost of technology, low product reliability, lack of effective standards and the low visibility of the technology. Given the uncertainty at this point it is unclear what the drivers of adoption will be in different regions, and where and how this adoption will occur. Furthermore, in many cases uptake of that technology has been linked to financial incentives offered by national governments and thus the technology is linked somewhat to political cycles which always shorter in duration the long term energy policy requires.

As with most renewable energy resources, MWTs are plagued by variability: the sun is not always shining, which means the wind is not always blowing. As such, accurately modeling future MWT output is quite uncertain. This analysis assumed a relatively low capacity factor of about 15%. capacity factor has a significant effect upon the calculations.

This technology is intrinsically linked to the local wind speed and hence local terrain and siting issues plus as a small scale technology it is highly dependent upon some form of financial subsidy due to the high installed cost per unit generation.

The largest drawback of MWTs is their high initial investment. As it stands, the payback period of most MWTs on the market is roughly equivalent to the lifetime of the machine itself. Worse yet, because the percentages and installed capacities of MWTs are so small, the RRS may not have enough finesse to accurately forecast the true cost of MWTs. Perhaps forecasts out 100 years with the same assumptions would show a more reasonable lifetime savings. Additional tax rebate programs or subsidies available to consumers will help prompt further adoption of MWTs.

Relatedly, the issue of energy storage is inherently intertwined with any microgrid application. When installing a MWT, it can either feed excess electricity back into the grid, or stored onsite. Indeed, more and more customers are gravitating towards onsite storage. Products that are just now entering the marketplace like Tesla’s PowerWall and Power Pack model battery storage systems for capable of storing up to 10kW-hr to hundreds of kWh respectively, would nicely complement the scales of energy generated by MWTs. As the developing world become more and more electrified, onsite storage begins to look more and more attractive. Instead of building expensive grids to interconnect remote villages, the excess electricity generated by MWTs can be stored onsite, in a battery pack.

## Benchmarks

No data sources were found that could be reasonably benchmarked to PDS micro wind turbines adoption till 2050.

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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. It is considered a global weighted averages for this input. This is used to estimate the **Replacement Time**.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**Regrets solution** has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

**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. World Wind Energy Association, ‘Small Wind World Report, 2016’ [↑](#footnote-ref-1)
2. The IPCC’s 5th Assessment Report analyzes the following sources: Coal: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2013a), IEA-RETD (2013), Schmidt et al. (2012), US EIA (2013). Gas Combined Cycle: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2011), IEA (2013a), IEA-RETD (2013), Schmidt *et al.* (2012), US EIA (2013). [↑](#footnote-ref-2)
3. 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-3)
4. In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary. [↑](#footnote-ref-4)