**Technical assessment for**

**Small Hydropower**

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Table of Contents

[List of Figures 4](#_Toc19233311)

[List of Tables 4](#_Toc19233312)

[Acronyms and Symbols 5](#_Toc19233313)

[Executive Summary 8](#_Toc19233314)

[1 Literature Review 9](#_Toc19233315)

[1.1 State of In-stream Hydro Technologies 9](#_Toc19233316)

[1.2 Adoption Path 14](#_Toc19233317)

[1.2.1. Current Adoption 14](#_Toc19233318)

[1.2.2. Trends to Accelerate Adoption 15](#_Toc19233319)

[1.2.3. Barriers to Adoption 17](#_Toc19233320)

[1.2.4 Adoption Potential 18](#_Toc19233321)

[1.3 Advantages and disadvantages of In-stream Hydro Systems 19](#_Toc19233322)

[1.3.4 Similar Solutions 19](#_Toc19233323)

[1.2.1 Arguments for Adoption 20](#_Toc19233324)

[1.3.5 Additional Benefits and Burdens 21](#_Toc19233325)

[2 Methodology 25](#_Toc19233326)

[2.1. Introduction 25](#_Toc19233327)

[2.2. Data Sources 26](#_Toc19233328)

[2.3. Total Addressable Market 28](#_Toc19233329)

[2.4. Adoption Scenarios 29](#_Toc19233330)

[2.4.1 Reference Case / Current Adoption 29](#_Toc19233331)

[2.4.2 Project Drawdown Scenarios 29](#_Toc19233332)

[2.5. Inputs 30](#_Toc19233333)

[2.5.1 Climate Inputs 30](#_Toc19233334)

[2.5.2 Financial Inputs 31](#_Toc19233335)

[2.5.3 Technical Inputs 33](#_Toc19233336)

[2.6 Assumptions 34](#_Toc19233337)

[2.7 Integration 34](#_Toc19233338)

[2.8 Limitations / Further Developments 35](#_Toc19233339)

[3. Results 37](#_Toc19233340)

[3.1 Adoption 37](#_Toc19233341)

[3.2. Climate Impacts 38](#_Toc19233342)

[3.3. Financial Impacts 40](#_Toc19233343)

[4 Discussion 41](#_Toc19233344)

[4.1 Benchmarks 42](#_Toc19233345)

[5 References 44](#_Toc19233346)

[6 Glossary 50](#_Toc19233347)

# List of Figures

[Figure 1.1 Hydro turbine classifications (Elbatran et al., 2015). 11](#_Toc44543745)

[Figure 1.2 Power density of water and wind turbines (Yuce and Muratoglu, 2015) 13](#_Toc44543746)

[Figure 1.3 Growth of Identified Small Hydro Potential in India (Mishra et al., 2015) 16](#_Toc44543747)

[Figure 3.1 World Annual Adoption 2015-2060 38](#_Toc44543748)

[Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction (2015-2060) 40](#_Toc44543749)

# List of Tables

[Table 1.1: Upper Limits of ISH (Abbasi and Abbasi, 2011) 9](#_Toc19233297)

[Table 1.2: Small Hydro Definitions (Mishra et al., 2015) 10](#_Toc19233298)

[Table 1.3 – Generation from ISH in 2015 (Source: IRENA,2017) 14](#_Toc19233299)

[Table 1.4 Water energy solutions versus conventional electricity generation technologies 23](#_Toc19233300)

[Table 2.1 Climate Inputs 31](#_Toc19233301)

[Table 2.2 Financial Inputs for Conventional Technologies 32](#_Toc19233302)

[Table 2.3 Financial Inputs for Solution 33](#_Toc19233303)

[Table 2.4 Technical Inputs Conventional Technologies 33](#_Toc19233304)

[Table 2.5 Technical Inputs Solution 33](#_Toc19233305)

[Table 3.1 World Adoption of the Solution 37](#_Toc19233306)

[Table 3.2 Climate Impacts 38](#_Toc19233307)

[Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq 39](#_Toc19233308)

[Table 3.4 Financial Impacts 40](#_Toc19233309)

[Table 4.1 Benchmarks 42](#_Toc19233310)

# Acronyms and Symbols

• AMPERE — Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates

• 5YP — Five Year Plans

• AC - Alternating Current

• BOS - Balance-Of-System

• CO2 — Carbon Dioxide

• CO2 eq. - Carbon Dioxide equivalent

• CPUC – California Public Utilities Commission

• DC- Direct Current

• DCF – Discounted Cash Flow

• DOE – Department of Energy (US)

• DS — Degree Scenario

• EIA – Energy Information Administration (US)

• EPBT - Energy Payback Time

• EROI – Energy Returned on Energy Invested

• ETOI - Energy Return On Investment

• ETP – Energy Technology Perspectives

• EU — European Union

• EV – Electric Vehicles

• GEM-E3 — General Equilibrium model for Economy, Energy and Environment

• GHG – Greenhouse Gases Emissions

• 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 on Climate Change

• IRENA – International Renewable Energy Agency

• ISH — In-Stream Hydro

• kW — Kilowatt

• kWp – Kilowatt (Peak)

• LCA – Life Cycle Assessment

• LCOE - Levelized Cost of Electricity

• LED – Light Emitting Diode

• LUT -Lappeenranta University of Technology

• MESSAGE-MACRO — Model for Energy Supply Strategy Alternatives and their General Environmental impact with macroeconomic feedback

• MIT – Massachusetts Institute of Technology

• MNRE — Ministry of New and Renewable Energy, Govt of India.

• MW – Megawatt

• MWp – Megawatt (Peak)

• NAFU - Net Annual Functional Units

• NAIU - Net Annual Implementation Units

• NOx - Nitrogen Oxides

• NPV – Net Present Value

• NREL - National Renewable Energy Laboratory (US)

• O&M - Operation and Maintenance

• OECD – Organization for Economic Co-operation and Development

• PD – Project Drawdown

• PDS - Project Drawdown Scenario

• PM2.5 - Particular Matter (2.5µm)

• PPA - Power Purchase Agreement

• PPB – Parts Per Billion

• PPM – Parts Per Million

• PV – Photovoltaic

• R&D — Research and Development

• REF – Reference Case

• REmap – Renewable Energy Roadmap (IRENA)

• REN21 – Renewable Energy Policy Network for the 21st century

• RES — Renewable Energy Sources

• ROR -Run of River

• RPO – Renewable Purchase Obligation

• RRS – Reduction and Replacement Solutions

• SCADA - Supervisory Control and Data Acquisition

• SEIA - Solar Energy Industries Association

• SO2 - Sulfur Dioxide

• SPV – Solar Photovoltaic

• TAM - Total Addressable Market

• TWh - Terawatt-Hours

• USD – United States Dollars

• WEO – World Energy Outlook (IEA)

# Executive Summary

Project Drawdown defines this solution as small-scale hydropower based electricity generation systems of capacities under 10 megawatts. In-Stream Hydrokinetic systems are included in this definition. Such systems have the potential to replace conventional electricity-generating technologies such as coal, oil, and natural gas power plants and hence are recognized as a “Solution” to the problem of global warming. In-stream hydro (ISH) projects, sometimes referred to as run-of-river (ROR) or simply small hydro projects (SHP), work on principles similar to large reservoir-based projects but do not divert or store large amounts of water. Another type of in-stream hydro works on tidal energy, where underwater turbines are anchored to the riverbed and generate energy from the flowing river current. This report focuses almost exclusively on the former type.

The total addressable market (TAM) for small hydropower is based on projected global electricity generation in terawatt-hours from 2020-2050, with current adoption estimated at 3.0 percent of generation. Impacts of increased adoption of in-stream hydro 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. Due to the uncertainty associated with the development of these technologies, the Plausible Scenario follows IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; IRENA (2018b) REmap Case scenario; and Equinor (2018) Renewal Scenario using a medium growth trajectory. *Drawdown and Optimum* Scenarios have similar adoption sources, though following high growth trajectory. The PD scenarios were obtained by employing a factor of 12% on total hydropower generation of the sources projections. This factor of 12% was derived by averaging the share of SHP in total hydro generation. This data, exclusive to SHP below 10MW (IRENA, 2017).

The results for the *Plausible Scenario* show that the net cost compared to the Reference Scenario would be US$49 billion from 2020-50, with nearly US$123 billion in net operating savings over the same period. Increasing the use of small hydropower generation as portrayed on the *Plausible* scenario would require an estimated US$295 billion in cumulative first costs. Under this scenario, the increased adoption of this solution could avoid 1.7 gigatons of carbon dioxide-equivalent greenhouse gas emissions from 2020-2050. The *Drawdown and Optimum Scenarios* result in 3.3 gigatons of avoided greenhouse gas emissions.

Small hydropower systems impose a smaller impact on aquatic ecosystems and local communities; but, like all forms of hydro-based generation technologies, they need to be carefully vetted as they cannot completely prevent stresses on ecosystems and human well-being. Small-scale hydropower has a wide range of designs, equipment, and material. In-stream hydrokinetic solutions, for example, might play a crucial role in remote mountainous regions in need of electrification where it is uneconomical to install power transmission lines. In-stream hydro offers a reliable and economical method of generating electricity in these remote places. Instead of building expensive electric transmission networks or transporting fossil fuel to run generators, the natural flowing rivers adjacent to so many of these villages can be harnessed to provide a clean and nearly endless supply of electricity.

# Literature Review

## State of Small Hydro Technologies

Effectively and safely harnessing the energy of natural resources is key to reducing carbon emissions associated with generating electricity for an ever-growing population. Though wind and solar have received the bulk of the attention of the proponents of clean energy, in-stream hydro (ISH) technology has also matured in recent years, rendering it no less deserving of the spotlight.

ISH falls under the broader category of "small hydropower." (SHP). The primary distinction between large, utility-scale hydropower and small hydro power is the presence of a reservoir (Blyashko, 2010). Large hydro power projects dam the waterflows, diverting and subsequently storing the water into reservoirs. This water can then be released through turbines in a highly controlled manner. Conversely, small hydro projects, oh the other hand, are passive systems, because they do not redirect or store large swaths of water (Blyashko, 2010). Rather, they are placed at the site of the running resource: hence the phrase "in stream hydro." The vast majority of small hydro projects are "in stream." (Paish, 2002). For reference, ISH is also commonly referred to as run-of-river (ROR). As per Project Drawdown's naming scheme terminology, this report will refer to this technology as ISH, but readers should be aware that many institutions use ISH and ROR interchangeably.

There is no internationally uniform denomination for categorizing small hydro power projects (SHP) or even ISH, and so its upper limit the range of sizes varies from country to country. Some countries peg the upper threshold of small hydro to systems no larger than at 25 MW (MNRE, 2012). whereas others have a more liberal definitions, wider classification expanding the limit to 50 MW (Pang et al., 2015). However, 10 MW total capacity is a widely accepted worldwide adopted figure and this will be used by the present report to define ISH. Table 1.1 showcases the upper limit specified by various governments countries.

Table 1.1: Upper Limits of ISH (Abbasi and Abbasi, 2011)

|  |  |
| --- | --- |
| **Country** | **Upper Limit (MW)** |
| UK | 5 |
| Sweden | 15 |
| European Small Hydropower Association | 10 |
| Colombia | 20 |
| Australia | 20 |
| India | 25 |
| China | 50(Pang et al., 2015) |
| Philippines | 50 |
| New Zealand | 50 |
| Brazil | 30 |
| Canada | 50 |
| EU | 20 |
| Norway | 10 |
| US | 5 - 100 |

Some agencies differentiate between small, micro and pico hydro. Table 1.2 illustrates how India’s Ministry of New and Renewable Energy (MNRE) demarcates small hydro projects:

Table 1.2: Small Hydro Definitions (Mishra et al., 2015)

|  |  |
| --- | --- |
| **Kind** | **Maximum Station Capacity (MW)** |
| Pico | 0 – 0.005 |
| Micro | 0.005 – 0.1 |
| Mini | 0.1 – 2 |
| Small | 2 – 25 |

There is no uniformity even within the US on the definition of “small hydropower”. The definitions vary from State to State and are defined in the range of 10 – 30 MW size. However, there is a growing consensus that projects below the size of 10MW should be considered as “small” as distinct from large hydro. The US Department of Energy, the United Nations Industrial Development Organization and above all – IRENA all go by this classification (Kelley-Richards, 2017).

Such fine detail is outside of the scope for this analysis, but is provided for the purposes of reference. At its most basic, ISH is a way of harnessing potential and kinetic energy: flowing river water is used to generate electricity, much like water wheels of yore. In fact, ISH is arguably one of the oldest and most reliable methods of generating electricity: the first hydrokinetic system in the US was installed in Wisconsin in 1882, just three years after Thomas Edison invented the incandescent lightbulb (Abbasi and Abbasi, 2011). Thus, it can be safely assumed that this is a proven and well-established technology.

Given the versatility of this “solution”, Drawdown's source of ISH is any kind of running water, even sewage water (assuming of course that the solids have been filtered out so as not to cause damage to any mechanical components). The vertical height through which the water falls while entering the turbine is called the “Head’. As discussed in greater detail below, due to the energy density and head of the water, what may appear as an "untappable" stream of water, may very well yield enough energy to generate a surprising amount of electricity.

In a typical ISH system, a portion of a river's water is rerouted at the diversion weir (a weir is a low dam intended to slightly raise the water level only to regulate the flow). Debris and particulates are filtered out at the forebay tank. Water then flows downward through a pressure regulated pipe called a penstock. The penstock's function is to regulate the flow of water to the turbine: a valve or sluice at the juncture of the forebay and penstock can temporarily halt flow to the turbine should it need maintenance or repairs. Upon exit from the penstock, the water flows through a turbine which is coupled with a generator which generates the electricity.

On exiting the turbine, the water then rejoins the rest of the river flow at the tailrace (Paish, 2002). The height through which this water falls during its passage through the system is called the “Head”. The head is thus a reference to the hydrostatic pressure potential of the ISH system and it determines the amount of energy that can be generated by the system.

Depending on the location of the ISH system, one of two types of turbines is utilized: impulse or reaction turbines. Within these two categories, there are several specific types of turbines, tailor suited for the specific application. Figure 1.1. outlines the classifications of these turbines. For example, the US Department of Energy’s Hydropower website, provides illustrations and examples of the various types of ISH turbines.

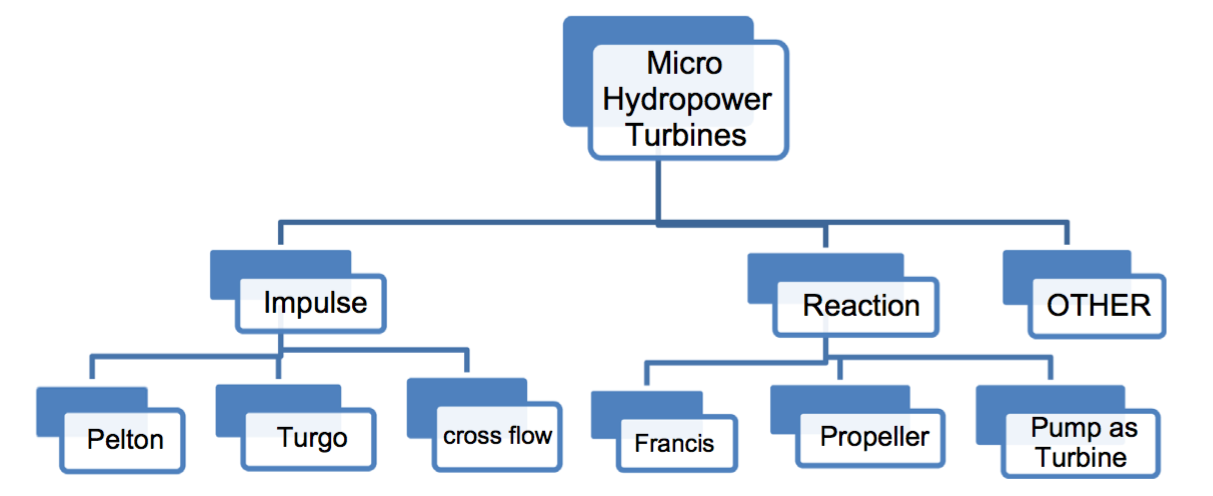


Figure 1.1 Hydro turbine classifications (Elbatran et al., 2015).

Impulse turbines have simple designs and are used in medium to high head applications, though they have recently been quite successful at low head ISH sites also (Elbatran *et al*., 2015). These are broadly classified as :-

* Turgo turbines: these are used for heads between 3 — 150 m
* Pelton turbines: these are well suited for large head and low flow sites
* Cross flow turbines, these can be used in horizontal or vertical configurations and are preferred for higher flow rate and low head sites as compared to either Turgo or Pelton turbines

As compared to impulse turbines, reaction turbines perform better in low head and high flow locations (Elbatran *et al*., 2015). These are classified as:

* Axial flow turbines which comprise the bulk of all reaction turbines, as their design is both proven and efficient.
* Francis reaction turbines have also witnessed widespread deployment in the hydroelectricity sector, as their design enables them to be installed at micro, medium or even large hydropower stations.
* “Pump as Turbine” comes into play when a pump is run in reverse to generate electricity.

The general formula for calculating the power generated by a hydro systems is (Mishra *et al*., 2015):

*P = rη*ρ*gQH (Equation 1)*

where

*P -*is the mechanical power output at the turbine shaft

η is the efficiency

ρ *-* is the density of water

*g-* is the acceleration due to gravity

*Q -* is the volume flow rate passing through the turbine

*H -* is the effective pressure head.

Effectively, all but the last two variables are constant. Thus the power produced by a hydro system is dependent on the flow rate, *Q,* and the pressure head, *H* of the water.This is the main reason why steep, high incline locations tend to be more attractive to ISH project developers. Typically, ISH plants are classified as "low" when *H* is between 2 m and 20 m, "average" when *H* is between 20 m and 150 m and "high" when *H* is over 150 m (Roque *et al*., 2014). The power extracted from the turbine is obtained via Equation 2, which is essentially a derived form of kinetic energy (Vermaak *et al*., 2014):

P*turbine* = ½ AρQ3cp *(Equation 2 )*

where

*Pturbine* is the power generated from the turbine

*A* is the turbine's cross sectional area

*ρ* is the density of water

*Q* is the flow rate

*cp* is the turbine efficiency

The so-called Betz Limit dictates that due to the laws of physics, the maximum efficiency of any turbine   
cannot exceed 0.59. Equation 2: is the same equation used to calculate the power from a conventional wind   
turbine. Though when comparing the power output between wind and hydro turbines, the medium in which the turbine is operating, plays an important role. The density of water being 1000 times higher than the density of air. Figure 1.2 depicts the flowrate, *Q* versus power density *(Pturbine/A)* for a wind turbine and a hydrokinetic (water) turbine and helps visualize the stark difference between the two.

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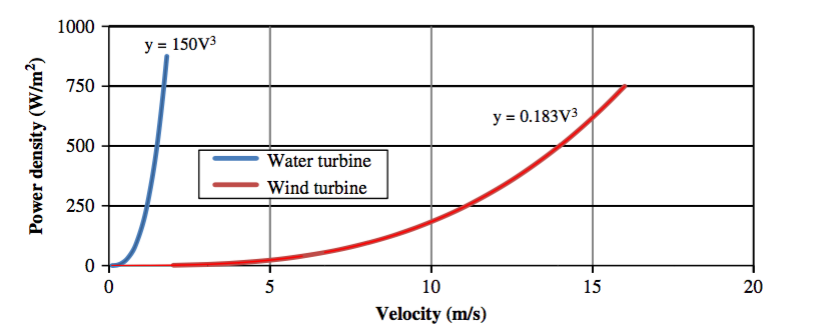


Figure 1.2 Power density of water and wind turbines (Yuce and Muratoglu, 2015)

Because of the vastly higher density of water, a substantially lower flow rate results in the same power output as, compared to a wind turbine. A flowrate with a density of 1,025 kg/m3 only is needed to have a velocity that is 10.6% of an air flow with a density of 1.22 kg/m3 to have the same equivalent power density (VanZwieten *et al*, 2015). This is another benefit of ISH systems, especially in locations with low flow: the applicability of the technology is not limited to only fast flowing rivers, as the density of water more than makes up for slow flowing rivers that ISH project developers would otherwise dismiss. Another advantage of the hydro turbines is that, unlike wind turbines, these are not limited to fast flowing rivers. Even slow flowing rivers and canals are suitable if they can provide a minimum head.

## Adoption Path

### Current Adoption

Current adoption of ISH is estimated at 676 TWh annually which accounts for 3 percent of the total global electricity generation. Due to ISH' s dependence on local geography and hydrology, there are only a handful limited number of places where the technology has been successfully adopted. Only nine countries have installed capacities of ISH over 1GW (IRENA, 2017). China (where the upper limit for ISH is 50MW) is way ahead of the field with almost 110GW of installed capacity. Out of this, only 39.8GW is categorized under 10MW. The Other countries having the bulk of the capacity include Japan, the United States, Brazil, Canada, the UK, China, Tibet and India and various countries of the EU, notably Italy, Norway and the UK. The adoption levels for ISH in these countries are as follows:

Table 1.3 – Generation from ISH in 2015 (Source: IRENA,2017)

|  |  |
| --- | --- |
| **Country** | **Generation from ISH (capacity of systems under 10MW) in 2015 (GWh)** |
| China | 401,531 |
| Japan | 16,469 |
| United States | 10,843 |
| Brazil | 20,399 |
| Canada | 5,192 |
| India | 4,328 |
| Italy | 10,864 |
| Norway | 7,846 |
| United Kingdom | 1,289 |

Due to ISH’s dependence on local geography and hydrology, there are only a handful of places where the technology has been adopted. The countries receiving the bulk of the attention are the United States, the UK, China, Tibet and India. China and India especially have made great strides in recent years to further develop the technology, as evidenced by India’s MNRE’s highly specialized classification of small hydro projects (see Table 1.2 above). One primary driver for this is due to ISH’s increasing popularity near rural areas. A major hurdle to China’s and India’s continued electrification is brining electricity to the hundreds of remote villages (Liu *et al*., 2013). ISH offers one of the best methods of delivering power to these areas. Typically located in mountainous regions near water, these locations are prime targets for ISH projects. The steep terrain does not lend itself towards electrification by conventional means: extending transmission lines is cost prohibitive (high line load losses and low power consumption, aside), as is transporting diesel fuel for generators. Therefore, ISH offers the most economic and reliable method of generating electricity in these places (Vermaak *et al*., 2014).

### Trends to Accelerate Adoption

In 2016, the global installed capacity has been estimated to be 78 GW registering a growth of 4% over the installed figure for 2013 (UNIDO, 2016). At the same time, the estimated potential of global ISH has also increased by 24% to 217GW thereby indicating a growth of 24%. Out of this potential, only 36% has been developed so far.

Concerted efforts are being made by different countries to accelerate the exploitation of this potential and this has been reflected in the generation figures. The global adoption level of ISH was 334.86 TWh in 2007 and this increased rapidly to 580.7 TWh by 2015 thus registering an annual growth of 73.4% over the period of 8 years (IRENA, 2017).

China and India especially have made great strides in recent years to further develop the technology, as evidenced by India's MNRE's specialized sub-classification of small hydro projects (see Table 1.2 above). Both countries have also set up specialized institutions to develop the small hydro sector. One primary driver for this is the suitability of ISH to provide electricity to remote and hilly regions Such areas are a major challenge to China's and India's electrification drive to bring electricity to the hundreds of remote and unelectrified villages (Liu *et al*., 2013). ISH offers one of the better methods of delivering power to these areas. Typically located in mountainous regions near flowing water, these locations are prime targets for siting ISH projects. The steep terrain does not lend itself towards electrification by conventional means: extending transmission lines is cost prohibitive (high line losses and low power consumption, aside), as is transporting diesel fuel for generators. The locations are mostly in eco-sensitive zones .Therefore, ISH offers an economic and reliable method of generating electricity in these places without causing too much harm to the sensitive eco-systems. (Vermaak *et al*., 2014).

Small hydro in China has a rich and varied history. Originally intended to electrify rural areas, the first small hydro project in China was installed in 1912. It took another century until small hydro began its current expansion and became a part of the country's domestic energy strategy. By the end of 2011, China had installed over 62 GW of small hydro (Panh *et al*., 2015). This translated to roughly 40% of the world's small hydro power capacity (Paish, 2002). Recent acceleration has brought this level to 109 GW by the end of 2015 (IRENA, 2017). Located in the western region of the country, Tibet is home to vast water resources and its rocky terrain, like Himalayan India, makes it a prime target for ISH development. Tibet is thus poised to receive the bulk of the attention as the China continues its "west to east" power transmission policy.

India’s MNRE disserves special mention for its work on ISH development. Electricity planning in India revolves around five year plans (5YP). The country is currently on its twelfth 5YP, aiming to source 2% (2,100 MW) of its electricity from small hydro projects by 2017. Given present trends, India needs to install 420 MW/year to meet this goal. For reference, during its previous 5YP, India installed 1,419 MW of small hydro against a target of 1,400 MW and the country is on track to meet its target for its current 5YP (Mishra et al., 2015). Indeed, small hydro potential in India continues to climb (see Figure 1.3).

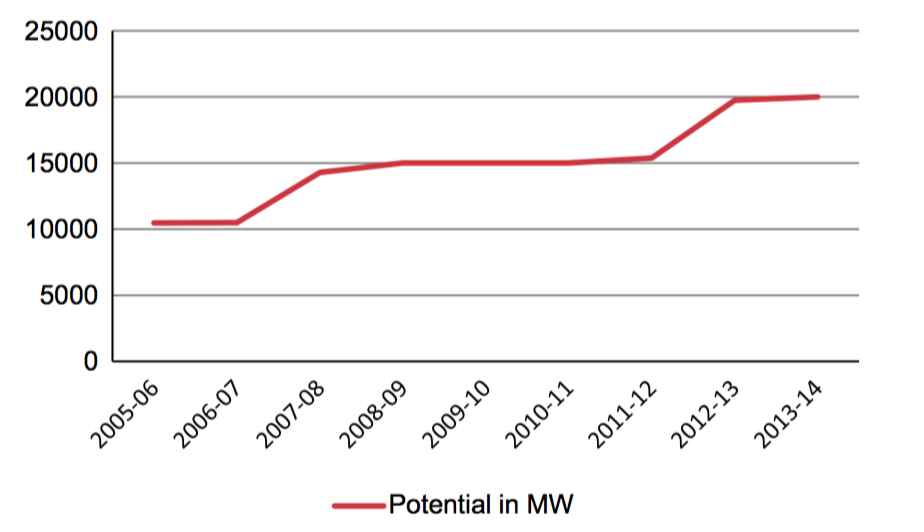


Figure 1.3 Growth of Identified Small Hydro Potential in India (Mishra et al., 2015)

Small hydro in China has a rich and varied history. Originally intended to electrify rural areas, the first small hydro project in China was installed in 1912. It took another century until small hydro began its current expansion and became a part of the country’s domestic energy strategy. By the end of 2011, China had installed over 62 GW of small hydro (Panh *et al*., 2015). This translates to roughly 40% of the world’s small hydro power capacity (Paish, 2002). Though it is the western portion of the country, namely Tibet, that is poised to receive the bulk of the attention as the China continues its “west to east” power transmission policy. Tibet is home to vast water resources and its rocky terrain, like Himalayan India, make it a prime target for ISH development (Zhang et al., 2015).

It is countries like India and China, with their rich hydrological resources and whose rapid population growth prompts expansive electrification, where ISH has been the most popular (Pang *et al*., 2015). Though interest and research on ISH remains prevalent in places like the US, UK and other European countries, these regions don’t face the same challenges as Asia: wide disparity between those with and without electricity due to the absence of sprawling, all-encompassing electrical grid.

In the US, ISH installed capacity is of the order of 3.7GW and it accounts for 0.4% of the country’s generating capacity (UNIDO, 2016). The US Department of Energy is making concerted research and developments to increase hydro power capacity though its Water Power Program and a long-term National Hydropower Vision.

Japan has an ISH installed capacity of 3.6 GW with 49 more plants totaling 54 MW are under construction. Similarly, Norway has an installed capacity of 2.24 GW and there is a concerted effort to develop ISH further with projects of almost 2GW under consideration of the licensing authorities.

The Clean Development Mechanism established under the Kyoto Protocol has come as a boost to developing ISH in the third world. Under this mechanism, developed countries could meet their emissions targets by funding the setting up of clean energy projects in developing countries. A 2007 study from India found that ISH emerged as one of the popular projects to attract carbon credits because of environmental benefits. The methodologies had been developed thus making ISH projects a preferred choice for many countries (Bajaj, 2007).

Of the 160 odd countries studied by UNIDO in 2016, about half had put in place various fiscal and financial incentives (like feed-in-tariffs) in order to attract investments into the ISH sector (UNIDO, 2016). It is therefore a matter of time before the sector enters a fast track of development. The ISH sector therefore provides both a challenge as well as an opportunity to accelerate its adoption.

### Barriers to Adoption

There is a wide range of existing barriers which prevent a rapid and widespread adoption of this solution. They can broadly be classified under different types – Environmental, Social, Economic, Technical and Administrative (Kumar and Katoch, 2015).

ISH carries with it some of the environmental burden of large hydropower projects. They are usually located in ecologically fragile areas and as the search for more potential intensifies, it is reaching pristine and untouched landscapes that support unique and sometimes rare flora and fauna. Construction of infrastructure at these sites usually involves felling of trees and this could lead to destabilizing fragile mountain faces. As such, ISH cannot always be said to be environmentally benign and each project needs a minimal impact assessment.

In some cases, the projects may involve relocating some local populations thus creating rehabilitation problems. The entry of forest loggers and others searching for medicinal and forest produce gets facilitated with roads and bridges. This can gives rise to social tensions, especially where the local population is aware of the downside of these developments. Communities hugging tress and generally protesting against hydro projects are not unheard of.

The technological aspects involved can also act as barriers to ISH. The first requirement is availability of long-term and historical flow data of the site. For this long-term studies on river basins have to be undertaken. This is a costly, long drawn-out and resource intensive exercise. Where this meta-data is not available, the sites have to be individually studied for at least two years and the electro-mechanical equipment has to be tailor-made to suit the site. Thus, the advantage of a “type” or set-model is usually not available for ISH. The problem gets aggravated in hilly sites and this increases the cost which may eventually affect the viability of the project.

Vagaries of water flow and geological surprises add to the economic viability of ISH. Non-availability of adequate water flow throughout the year seriously affects the financial viability of these projects. Bankers and other financial institutions do not have the experience of funding such projects and these are thus seen as risky propositions raising the financing costs and further creating hurdles to their rapid adoption.

Lastly are the administrative problems associated with these projects. A variety of permissions and licenses could be required before such projects come on-stream. Like most other renewable energy projects, ISH requires financial and fiscal incentives to take-off. These could be in the form of tax-breaks, feed-in-tariffs, renewables purchase obligations etc. Where these are not available, ISH finds it difficult to stand on its own.

### Adoption Potential

An interesting feature of the global ISH potential is that all has not been fully discovered or firmly established as yet. A comprehensive 2013 UNIDO Report on small hydro put the global potential at 173GW at the end of 2012. This was arrived at by aggregating data from 152 countries. However, the cumulative figure came with a rider that since the data was sourced from a wide variety of sources, there was a possibility of “potential compromise of data integrity to varying degrees” (UNIDO, 2013). One of the reasons was that data on economically viable potential was readily available from the developed countries whereas the same was not the case for many countries from Africa, Asia and South America. The report did not rule out the possibility of identification of more ISH potential in future.

A second UNIDO report of 2016 has estimated this potential at 217 GW which is an increase of almost 24% in three years (UNIDO, 2016). One reason for this increase is that the search for exploiting ISH potential is spreading as a source of clean energy for remote areas. More and more countries are coming on board to develop ISH. The first step is identification of technically feasible sites. Surveys are now venturing into increasingly inaccessible areas and covering hitherto unsurveyed river basins. As more and more sites get identified, the tally is set to increase. A linear extrapolation of the trend indicated in the UNIDO Report (UNIDO, 2016) takes the total potential by 2050 to around 730 GW.

Additions to irrigation networks across the globe also offer potential low-head sites which did not exist before. And these have the added economic benefit of providing sites that have water flow throughout the year as opposed to snow-fed hill streams. Also a mention needs to be made of the latest technological tools being deployed to identify potential sites. Satellite surveys and GIS mapping of interior river basins reveal many potential sites that could not be easily reached before. In short, there is still a large potential for ISH left to be discovered.

The 2016 Report by UNIDO had assessed that by 2015, only 78,306 MW potential had been exploited out of an estimated 2,17,096 MW. This works out to 36% - thus giving an indication of how much more can be exploited (UNIDO, 2016). An interesting fact brought out by this report is that the share of ISH potential throws up some telling regional differences. Asia has 55% of the global potential of ISH but it has so far exploited only 50% of this potential so far. Europe on the other hand has only 18% of the potential but has already exploited 85% of this. The Americas are yet to exploit 26% of their potential. Possibility of identifying more potential especially in Asia and the Americas is thus fairly bright.

## Advantages and disadvantages of In-stream Hydro Systems

### Similar Solutions

There are several solutions in the electricity generation sector that can replace conventional electricity-generating technologies such as coal, oil, and natural gas power plants which could be considered as similar/analogous solutions. Technologies similar to instream hydro that use the same resource: i.e. large hydro systems for electricity generation could offer a similar solution but the environmental, social and economic impacts are so high that these are not considered as an alternative to small hydro. Large hydro systems are not considered as a Drawdown solution due to their enormous environmental and social impacts.

Though there are other solutions like wave and tidal energy but these are based on the sea and ocean water and its waves and tides. Moreover, all these differ from the ISH solution either in the level of agency (e.g. community or utility-scale level) or in the way the technologies work. Hence, strictly speaking, they are not being considered for the purpose of classifying them as solutions “similar” to ISH.

16

### Arguments for Adoption

First and foremost, the primary benefit of ISH are is that its low there are no carbon emissions during its operation. Moreover, there are no variable operational costs as the water flow come free. Hence, like with many other renewable energy sources, ISH is also characterized with having high upfront capital costs and low operating costs (IRENA; 2012). But, as compared to wind and solar sources, generation from ISH is much more predictable, as the latter it is not plagued by finicky winds or transient clouds. Additionally, ISH is able to generate electricity 24 hours a day if the water flow is there: And the rivers keep flowing even on breezeless days and moonless nights (Ardizzon *et al*., 2014), with the exception of the winter lean seasons in some locations.

As has been said earlier, ISH offers one the best a good methods of electrifying rural areas where it is uneconomical to install draw long power transmission lines. As an added benefit, since electricity is generated-on site, there are minimal losses that would otherwise be incurred from in transmitting the electricity power over long distances (IRENA, 2014).

Compared to its big brother – the large hydro, the ecological impact of ISH is substantially smaller: no large damming of hydrological resources is required. Rather, ISH, by its very nature, is a passive system, designed to complement the surrounding area, as opposed to drastically altering it (Svensson, 2000). From an engineering perspective, ISH turbines tend to have higher capacity factors. Compared to wind energy, ISH turbines require substantially slower flows to extract similar power outputs (Ardizzon *et al*., 2014).

An important metric for measuring the cost of energy from a particular project over its lifetime is the Levelized Cost of Electricity (LCOE) generated by the project on a per-unit basis. For this, the net present value (NPV) of various capital and operating costs is calculated to arrive at a consistent basis for comparing costs. The LCOE becomes a useful tool for comparing energy costs produced from different sources. In the case of ISH, it becomes even more important because though the first costs for ISH are high, there is hardly any operating cost as the “fuel” (i.e. water) comes free of cost. As a result of this, the LCOE becomes quite favorable when compared with fossil-based projects that have to grapple with ever increasing fuel prices (and pollution) throughout their lifetimes. Hence, though investment in ISH projects may seem high initially, they become much cheaper over their lifetimes. The returns become even more favorable once the environment and carbon abatement costs are built into the equation. In a study on small hydro, IRENA found that the LCOE of small hydro projects ranged from US$ 0.023/kWH to US$ 0.11/kWH while that of new large hydropower projects in the US ranged between US$ 0.02/kWH to US$ 0.085/kWH (IRENA, 2012). A recent LCOE study by Lazard had estimated LCOE for wind energy to be in the range from US$ 0.029/kW to US$ 0.056/kW. For a coal fired plant this would range from US$ 0.060/kW to US$ 0.143/kW (Lazard, 2018).

An under touted advantage of ISH, is its minimal consumption of water. As summarized by in a paper (Sachdev et al., 2015): "Where a small hydropower resource exists, experience has shown that there is no more cost-effective, reliable and environmentally-sound means of providing power than a small hydropower system. There are many hilly or mountainous regions of the world where the grid will probably never reach, but which have sufficient hydro resources to meet basic domestic needs of the local populations." In such situations, the argument for adopting ISH becomes strongest.

### Additional Benefits and Burdens

Apart from the basic objective of providing quality power to the neighboring communities which are generally remote and far away from the grid, there are many co-benefits which accrue to the communities when ISH is adopted as a solution. Some of these benefits are common to other forms of renewable energy solutions as well.

The first is the reduction in the scale of deforestation. ISH projects are generally located in regions having rich forest/biodiversity resources and the local populations utilize these for their day to day energy needs. This creates pressure of fuelwood extraction adversely impacting the region’s bio-diversity and reducing its carbon absorption capacity as a carbon sink. Also, the dependence on fossil fuels ( especially kerosene) to light lamps and stoves gets reduced to a large extent thus reducing the carbon emissions (GEF, 1992).

Another benefit is the impact on health of the communities, especially women. They are provided with a clean source of cooking energy and are no longer required to work in some filled kitchens In addition, their drudgery gets reduced if the ISH provides piped water to their homes. They do not have to trudge long distances to draw water and fuelwood for their homes.

Many countries have the legacy of water-mills which were used to provide mechanical power for various local uses like grinding wheat etc. ISH replaces these antiquated equipment with modern machinery adding to the efficiency of the power extraction.

There are some other spin-offs as well from ISH projects. After the projects are set up, the operation and tariff collection is many a time left to the local communities. This builds capacity and confidence among the communities and also provides them with some entrepreneurial skills as small shops come up around these projects. Quality of life improves as there is light in the evening and there is added time for studying and entertainment through TV, etc.

ISH is not, however, without its drawbacks. There is a lack of sophisticated modeling and simulation tools available to ISH project developers. As a result, for a new site, the developers have Factors to consider and calculate all parameters afresh when siting ISH plants include (Zeman et al., 2016). This not only adds to the technical complexity of setting up the plant, it also prevents ISH from taking advantage of scale by large scale manufacture of “type” equipment.

Though ISH is more reliable than other forms of renewable energy, RoR cannot maintain firm capacity—rivers are dependent on snow melt, which is seasonal. Vagaries of rainfall and associated landslides can upset the working of ISH. This impacts the flowrate, which in turn means that power output is variable and this can adversely affect the financial viability of the project and its operation (Mishra et al., 2015).

Though ISH systems do not dam large amounts of water, that does not mean they have *no* impact on the local hydrology. RoR is predicated on diverting a portion of the river through a man-made turbine, which will have some ecological impact on the surroundings. One extreme example showed that 70-80% of stream water was diverted at a RoR installation in China, significantly impacting macroinvertebrate density, richness and diversity. Macroinvertebrates are an important component of freshwater ecosystems, and widely used as a proxy for environmental and ecological health in freshwater ecosystems (Wang et al., 2016). Furthermore, the lack of scientific literature supporting the purported minimal adverse ecological impacts is scarce. Many assume that because ISH systems are small, their ecological impact will be proportionally small. Several agencies have enumerated many potential adverse impacts which need to be considered for ISH projects (Abbasi and Abbasi, 2011):

* Minor alterations to stream flow could cause flooding or negatively impact an area’s natural flood control mechanisms. This may prove deadly in rural regions not protected by man-made flood control measures like dykes or levees. The ecology of an area around a low-head scheme can also be affected permanently by the establishment of a mill-pond behind the dam.
* Indigenous fish populations may be harmed or even replaced. Nitrogen super-saturation, which causes gas bubble disease in fish, can occur in high-head schemes if large air packets are diverted along with the river water. Additionally, ISH installations can create or increase obstruction to fish migration routes.
* Flow reduction in high head schemes could cause water quality deterioration or increased pollution at both the abstraction point and where the water returns to the primary source.
* Hydro schemes may change the level of suspended solids in the river water and affect siltation, erosion, visual amenity and aquatic ecosystems.
* Threat of pollution from wastes due to running the ISH plant.
* Because of their smaller size, ISH plants have higher $/kW costs.

All of these potential (and arguably major) drawbacks are presupposed to be likely small and localized, provided best practice and effective site planning are used. However, taking into considering all factors, it can still be said that:

“By all reasoned assessments the environmental problems caused by small hydro look small in comparison to large hydro only till they are considered on the scale of impact per kilowatt of power generated. Once this is done, it emerges that the problems that would be caused due to widespread use of SHS would be no less numerous, and no less serious, per kilowatt generated, than those from centralized hydropower.” (Abbasi and Abbasi, 2011). Table 1.4 presents a comparison of selected pros and cons of the solution with others in the same sector and with the same energy source.

Table 1.4 Water energy solutions versus conventional electricity generation technologies

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Conventional Electricity Generation Technologies** | **Small Hydro** | **Large Hydro** |
| *Greenhouse Gas Emissions* | Extremely High | Almost Zero | Almost Zero |
| *Land Requirement* | Medium | Very Low | High |
| *Air Pollution* | Extremely High | Almost Zero | Almost Zero |
| *Electricity Generation Flexibility* | Very High | High | High |
| *Resource Extractive Drawbacks* | Extremely High | Low | Medium |
| *End of life Disposal Drawbacks* | Very High | Low | High |
| *Gestation Period[[1]](#footnote-2)* | Very High | Medium | High |
| *Modular Scalability[[2]](#footnote-3)* | Low | Low | Low |
| *Environment/Health Benefits* | Very Low | High | High |
| *Operation and Maintenance Costs* | High to Very High | Low | 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 adoption of both conventional technologies and the present solution (In-stream Hydro) 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 instream hydro systems. The model used for this analysis constructs both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for In-stream Hydro. Following project Drawdown methodological assumptions (further description available on the Drawdown RRS Model Framework and Guide), and in order to grasp the total impact of an increased adoption of the solution during the assessed time frame, the REF scenario assumes the future rate of adoption of In-stream Hydro remains fixed at the current year (i.e. 2018) level of the Total Addressable Market (TAM), estimated at 3.00 percent of electricity 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 developed alternative PDS scenarios, draw on existing adoption scenarios for Hydro systems 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 in-stream hydro power, 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 mode to evaluate the adoption of In-Stream Hydro 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, a variable meta-analysis of existing literature was conducted to create low, high, and mean estimates. For each solution variable, a sensitivity analysis of, on average, 13 data points reported in the literature was conducted. In some cases as many as 22 data points were considered. This allowed a robust and reliable analysis of financial, technological and climate parameters. These represent both optimistic and conservative estimates for the future costs and benefits of adopting this solution.

Several reports provide first installed costs for ISH. Not surprisingly, compared with large, reservoir hydropower, ISH has a lower first installed cost: capital costs are much less intensive, thus ISH projects face lower economic barriers to market entry. Depending on the region the costs may have significant variations and Smaller capacity systems carry a higher install cost, therefore several sources/regions and sizes were included in this analysis to determine the average capital cost of in-stream hydro systems installations (Navigant, 2009; IPCC, 2011; IRENA, 2012; JRC, 2014; Kumar, 2015; IRENA, 2015; IFC, 2015; NREL, 2018; IRENA, 2018; Kurup, 2018).

ISH carries a higher installed first cost than some other renewables. On the other hand, this technology is highly region dependent, the advantage being that electricity is generated on-site for a particular area, reducing, or even nullifying, the need for significant electrical transmission and distribution networks. Moreover, ISH projects have the biggest potential where rivers flow fastest, usually in areas with steep terrain. These areas make generation and transmission installations difficult, putting an additional premium on the electricity generated. Cost estimates for fixed and variable operation and maintenance (OM) of in-stream hydro were collected from several sources (e.g. IRENA, 2012; JRC, 2014; IRENA (2018a); NREL (2018)). These estimates were used to calculate total operating costs of in-stream hydro adoption, which, combined with capital costs for installation, represent the total financial costs of adopting this solution in the PD scenarios. 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 for conventional systems was calculated considering average prices for coal, oil and natural gas from 2005-2014 using IEA data (IEA, 2016a).

The lifetime of in-stream hydro systems that has been presented in the literature shows a wide variation (from 20 to around 60 years), is dependent on the type of technology being depicted. According to IPCC (2011), the lifetime of these technologies before replacement varies from 40 years to a maximum of 80 years; JRC (2014) presents 60 years for hydropower systems less than 10MW and alos for run of river technologies. Other sources as InstreamEnergy (2015) and Kusakana (2008) have reported figures of 20-25 years old. NREL reported a figure of 30 years based on real life decommissioning of an ISH project (NREL, 2018).

In order to compare capital and O&M costs of In-Stream systems adoption in the PD scenarios with that of conventional generation technologies, the cost data was obtained for fossil fuel-based electricity generating sources from the IPCC 5th Assessment Report (IPCC, 2014) which has conducted its own sensitivity analysis of a number of sources from the literature[[3]](#footnote-4), and other sources such as OECD (2015), and 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 obtained. These weights are based on the percentage, for each fuel on the total global electricity generation for 2014 (World Bank, 2015).

In order to calculate the total impacts and benefits of increased solution adoption (for the PDS scenarios), technical data was also integrated, including average annual use, plant lifetime, and average efficiencies. All three of these are key to determining the variable O&M 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 rate. Average plants efficiency is calculated from several global sources (IPCC, 2014; IEA, 2010), as well as from the U.S. EIA (2015).

Though the average annual use of conventional generating technologies is higher than that of in-stream hydro, the range of capacity factors for different conventional generating sources can still vary based on type of technology and location. For this reason, data was collected from a range of different sources (EIA, 2016; IEA, 2016b; Lazard, 2016) that represent most of the regions contained in this analysis. Capacity factor data for small hydro systems was available for the US, China, EU, India, Latin America, other world regions as well as globally (*e.g.* IPCC, 2011; REN21, 2016) which enabled the calculation of the average annual use of in-stream technologies for the world.

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 In-stream hydro plants. 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 in-stream hydro systems—primarily those lifecycle emissions associated with manufacturing, transporting, installing and other non-generation activities— peer-reviewed lifecycle analysis (LCA) studies for the different types of In-Stream and small hydro technologies available in the market were analyzed (e.g. Varun (2009), Masanet et *al*. (2013), NTEL (2013), Garcia Pang *et al.* (2014), and Gusano e*t al.* (2016)).

## 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

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world were expected, 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) case scenario, adoption is fixed at the current adoption[[4]](#footnote-5) (in percentage terms) of the market. That is, the current percentage of total electricity generation (TWh) provided by In-stream Hydro Power systems has been kept constant throughout the study period to 2050. As the market grows, the total number of In-stream hydro plants adopted grows equally to maintain the percent adoption estimated at its starting value in 2018. It is acknowledged that this, in reality, may not be a “business as usual” trajectory considering the changes taking place worldwide, but it allows a sort of measure to evaluate the impact of recent and even more aggressive policies to reverse global warming.

### 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. These are:

#### 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 in-stream hydro, this scenario is based on the evaluation of yearly averages of five optimistic scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; IRENA (2018b) REmap Case scenario; and Equinor (2018) Renewal Scenario using a medium growth trajectory.

The scenario herein described for this solution was obtained by employing a factor of 12% on total hydropower generation of the sources projections. This factor of 12% was derived by averaging the share of SHP in total hydro generation. This data, exclusive to SHP below 10MW, was obtained from IRENA (2017) RE Statistics 2017.

#### 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 this solution, the Drawdown Scenario is derived from the evaluation of the same scenarios as the Plausible scenario, though using a high growth trajectory. As described above, none of the sources above explicitly identify the evolution of small hydro systems for electricity generation; therefore, a conservative assumption was adopted that, in the future, the current share of 12 percent of all hydroelectricity would continue to come from small systems.

#### 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 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 follows the trajectory of ambitious scenarios with a high growth as above mentioned.

## 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, the In-Stream hydro electricity generation was estimated globally and regionally from 2020-2050. Thereafter, the emissions reductions due to the replacement of conventional electricity generation sources with the solution were calculated. The detailed methodology of these calculations is available at the Project Drawdown Integration Methodology report.

While being a renewable energy technology, In-stream hydro plants do not have direct emissions attributable to combustion of fossil fuels. However, the Project Drawdown modeling exercise considers the analysis of indirect emissions related to the different factors that indirectly contribute to GHG emissions from the life-cycle of in-stream hydro systems. In modeling the lifecycle emissions of In-Stream hydro adoption in the scenarios, a fixed value (t CO2-eq per TWh) was used factoring in information from several In-stream technologies rather than using a weighted average for different types of hydro systems in use. The climate results would therefore be expected to be more conservative than would have been the case if a decreasing average lifecycle emissions value for this solution was assumed.

The values collected in the RRS model show lifecycle GHG emissions for a range of different In-stream hydro technologies across different regions and system sizes. The analysis draws from research papers and reports that have estimated GHG emissions for small hydro systems. These have ranged from 3 to 237 g CO2eq/kWh over their lifetime. The wide span in results for in-stream hydro reflects different assumptions around type of technology, capacity factor, conversion efficiency, operating lifetime. Table 2.1 presents the boundaries of the data boundaries on the model and the selected model input.

Table 2.1 Climate Inputs

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Indirect CO2 Emissions (Solution) | *t CO2-eq/TWh* | 500-65,573 | 24,689 | 26 | 14 |

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[[5]](#footnote-6).

### Financial Inputs

The RRS model constructs PDS adoption scenarios for In-stream hydro electricity generation globally and regionally for each year until 2050. It has modelled both the capital costs and the fixed and variable O&M 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 In-stream Hydro electricity generation, along with first costs (per functional unit), were calculated. A lifetime capacity of 82,886 hours (around 43 years) was calculated depending on the average powerplant annual use.

For the solution (i.e. In-Stream Hydro), 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.

A mean value of the data set range collected is assumed for installation costs of in-stream hydro systems which results in a total first cost of US$ 2,785 per kilowatt[[6]](#footnote-7).  Estimates in the literature for the learning rate for this solution are scarce (e.g. Jamasb, 2007; Partridge, 2013; Arias-Gaviria, 2017); an average learning rate of 6.38% was used in the calculations; and this has the effect of reducing the installation cost to US$2,668 per kilowatt in 2030 and to US$2,612 in 2050, compared to US$1,786 (in 2014) per kilowatt for the conventional technologies (i.e. coal, natural gas, and oil power plants).

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.

Tables 2.2. and 2.3 depict the dataset ranges and the model inputs for the conventional and solution technologies.

Table 2.2 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 2.3 Financial Inputs for Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| First costs (Solution) | *US$2014/kW* | 1,126 – 4,445 | 2,785 | 50 | 17 |
| Fixed Operation and Maintenance Costs (Solution) | *US$2014/kW* | 25.17 – 150.96 | 88.06 | 22 | 8 |
| Variable Operation and Maintenance Costs (Solution) | *US$2014/kWh* | 0 – 0.006 | 0.003 | 5 | 4 |
| Learning Rate Factor (Solution) | % | 0 – 15.9 | 7.2 | 8 | 5 |

### Technical Inputs

Table 2.4 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 2.5 Technical Inputs Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Lifetime Capacity (Solution) | *hours* | 118,549- 247,222 | 182,885 | 16 | 11 |
| Average Annual Use (Solution) | *hours* | 3,197 – 5,224 | 4,210 | 41 | 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. It is assumed that this solution encompasses all types of small-scale hydropower technologies under 10 megawatts, including in-stream hydrokinetic systems.
2. ISH will replace conventional fossil fuel technologies being currently used in remote areas. Many places are using expensive and polluting diesel for power generation. ISH will be a cheaper and more secure source for these communities as a replacement. ISH will also continue to be implemented in rural areas that have yet to be electrified and also on irrigation canals which offer suitable heads.
3. Due to the lack of disaggregated data on ISH or small hydro systems for its long term development, in some scenarios available in the RRS model adoption dataset, the current and future share of small hydro generation has been derived from the aggregate total hydro generation by using the historically validated factor of 0.12 as the share of ISH in total hydro generation.

## 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 is available at [www.drawdown.org](http://www.drawdown.org). Those general notes are excluded from this document but may be referred to 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.

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

Through the process of integrating concentrated solar power 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

As is the case with many of the solutions Drawdown is investigating, access to robust data sources proved difficult. Though the literature on large-scale hydropower is abundant, rarely to major research outlets separate hydropower between large, reservoir style and small/RoR type. Since ISH is so dependent on geography, finding accurate global values of installed ISH was not easy. A handful of countries are regions are currently dominating ISH development, namely China and India, and most of the current literature is focused on those countries. It would be necessary for energy data collecting organizations like IRENA, IEA, EIA, UNIDO, etc., to step into this area of weakness and build up a database for ISH by performing a bottom-up data collection and update it regularly so that the progress of development in the field of ISH can be evaluated.

A major barrier to the widespread adoption of ISH is the lack of institutional finance being made available to set up projects in the field. There is a general lack of awareness about the potential of ISH and also risk aversion among the various bankers and investors. It therefore becomes necessary for making the financial institutions aware of the potential as well as the risks so that the social and environmental benefits of ISH can be brought out.

On the technical side, what has been happening is that the electro-mechanical equipment being deployed is simply a miniaturized version of the large hydro projects. As a result, each site requires detailed hydrological studies for long periods of time before the machines can be designed. Concerted R & D efforts are necessary to see that ISH is not beset with the lethargic design and manufacturing problems of large hydro. Since these are much smaller in size, attempts should be made to have smaller and modular types of designs so that these can be deployed with a minimum amount of fuss. This would be make a project less costly as well as speedy to implement.

Automation is the name of the game where technical prowess exists and manpower is difficult to come by. The ISH projects are amenable to automatic operation as these systems have been tried out in some countries. Where a large number of small units are planned on a single or nearby streams, automation could reduce O & M costs and SCADA systems could make technical and financial data easy to collect and collate.

It was assumed that ISH will be replacing mostly conventional electricity generation technologies. It is also expected that it could be a major solution for new rural electrification systems. Additional research needs to be done to determine what percentage of ISH that is actually replacing current fossil-fuel based methods of generating electricity and for new electrification. Because this solution has a relatively small impact (compared to major Drawdown solutions in this sector – e.g. Utility Scale Solar or Wind Onshore), thus altering the ISH projections may not have a significant impact. Nevertheless, it would be better to verify this assumption.

# Results

In the following section selected results derived from the RRS model are depicted evaluating the impact of increased adoption of In-stream hydro technologies for electricity generation as compared to conventional technologies.

## Adoption

A comparison of the results from the three modeled scenarios to the Reference Scenario allows an estimation of the climate and financial impacts of increased adoption of in-stream hydro systems. As a result of this exercise, the Plausible Scenario (PDS1) projects 1.99 percent of total electricity generation worldwide coming from in-stream hydro systems by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3), the market share reaches 1.6 percent with a significantly higher total electricity generation. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percentage terms. Figure 3.1 depicts the long term pathway trajectories for the different scenarios of in-stream hydro plants.

Table 3.1 World Adoption of the Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| **Plausible** | **Drawdown** | **Optimum** |
| In-Stream Hydro Systems | *Electricity Generation (TWh)* | 548 | 994 | 1,136 | 1,136 |
| *(% market)* | 2.4% | 2.2% | 1.6% | 1.6% |

Figure 3.1 World Annual Adoption 2015-2060

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore the operation costs reduction over time for both scenarios are 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 1.7 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. The Drawdown and Optimum scenarios result in higher growth of in-stream hydro technologies, with impacts on greenhouse gas emissions reductions over 2020-2050 of 3.3 gigatons of carbon dioxide-equivalent. Tables 3.2 and 3.3. provide additional information on the climate impacts of the solution adoption.

Table 3.2 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*** | 0.09 | 1.69 | 0.09 |
| ***Drawdown*** | 0.16 | 3.29 | 0.16 |
| ***Optimum*** | 0.16 | 3.29 | 0.16 |

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 suffered minor changes with 1.67 gigatons of carbon dioxide-equivalent in the *Plausible* scenario and 3.26 gigatons of carbon dioxide-equivalent for the Drawdown and *Optimum* Scenarios. Figure 3.2. show the world annual emissions reduction trajectories for the different scenarios for the long term.

Table 3.3 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** | 0.14 | 0.007 |
| **Drawdown** | 0.27 | 0.012 |
| **Optimum** | 0.27 | 0.012 |

Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction (2015-2060)

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore the operation costs reduction over time for both scenarios are overlaid in the figure.

## Financial Impacts

The financial impacts incurred by replacing conventional grid electricity sources with in-stream hydro systems are significant. The Plausible scenario presents US$49 billions of marginal first costs and over US$123 billions of net operating cost savings are projected over 2020 to 2050. PDS2 and PDS3 results show near US$80 billions of marginal first costs and US$237 of net operating savings.

These systems are typically installed in remote regions, an already expensive proposition. Furthermore, like with wind energy, small, singular capacity systems tend to carry a higher output cost. Grouping systems in aggregate tends to lower the cost per kWh. Unfortunately, this is not how ISH systems are deployed. A single ISH system is designed to provide electricity to a whole region. So while the system’s initial cost may be high, it could be possible to mitigate those costs by spreading them out across all the people who would benefit from having such a system installed. The capital costs for PDS adoption of in-stream hydro systems will require significant investments, as the cumulative capital costs are over US$295 on *Plausible Scenario* to US$375 billion on the more adoption ambitious scenarios. 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 3.4 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** | 294.59 | 49.36 | 122.8 | 22.76 |
| **Drawdown** | 375.62 | 80.07 | 237.2 | 47.10 |
| **Optimum** | 375.62 | 80.07 | 237.2 | 47.10 |

Figure 3.3 World Operating Cost Reduction (2015-2060)

# Discussion

In-stream hydro system offers several benefits including: 1,000x higher energy extraction rate from water as compared to wind, a resource that is easily predictable, it is a proven technology and has minimal ecological impact. Some of these cannot be understated, especially the predictability of the resource, an issue that constantly plagues the wind and solar industries. While some impact could be on the ecology of the areas contiguous to the ISH project, the project itself can be seriously affected as climate change could threaten the availability and seasonal distribution of water in some water sensitive locations.

Regarding the costs, ISH systems are, and will continue to be, installed in remote areas, most of which have yet to be fully electrified. This is an expensive undertaking and requires savvy financial planning, significant political capital, and a bit of luck. Focusing just on the final dollar amount masks several hidden (i.e. external) costs, which have been highlighted by this report. One prime example of these external costs is air pollution. Installing an ISH system may carry a higher upfront cost (and could even be more expensive to operate on a yearly basis). But this prevents the need to finance programs to combat health-related issues caused by air pollution from a system operating on fossil fuels. Another external cost would be the financial impact for the need to constantly transport and refuel a system run on fossil fuels. So although the bottom line financial metrics seem to suggest that ISH may not be offering a high rate of return, a better approach would be to assess the cost of the project by factoring in all the external environmental costs and carbon abatement benefits (namely the benefits of CO2 reductions).

Functional benefits of the technology aside, though, ISH one of the few solutions where the best resource is assuredly near the areas where electricity is needed the most. Mountainous regions, especially in India and China, prove to house the best ISH resource. And it is these areas that are, or will be, in need of electrification in the coming decades. ISH offers the most cost effective and appropriate technology for bringing electricity to these regions, as installing long electricity distribution networks or trucking in diesel for generators is too costly, burdensome and unreliable. The flowing rivers adjacent to where many of these areas’ indigenous peoples call home, will prove to be the best resource for generating electricity.

## Benchmarks

Table 4.1 depicts a benchmark of Project Drawdown results for 2050 of the in-stream hydro solution, on the three developed scenarios to other six publicly available scenarios from IEA (2016b) and Greenpeace (2015). Due to a lack of specific information for ISH, the benchmarked results account for all hydro power electricity generation projected for the year 2050.

Table 4.1 Benchmarks

|  |  |  |
| --- | --- | --- |
| **Source and Scenario** | **Electricity Generation in 2050 (TWh)** | **Market Share in 2050 (%)** |
| **Project Drawdown – Plausible Scenario (PDS1)** | **994** | **2.2%** |
| **Project Drawdown – Drawdown Scenario (PDS2)** | **1,136** | **1.6%** |
| **Project Drawdown – Optimum Scenario (PDS3)** | **1,136** | **1.6%** |
| IEA Energy Technologies Perspectives (2016) – 6DS | 6,228[[7]](#footnote-8) | 12.08% |
| IEA Energy Technologies Perspectives (2016) – 4DS | 6,655 | 14.22% |
| IEA Energy Technologies Perspectives (2016) – 2DS | 7,443 | 17.91% |
| Greenpeace Energy [R]evolution (2015) – Reference Scenario | 6,431 | 12.83% |
| Greenpeace Energy [R]evolution (2015) – Energy Revolution Scenario | 4,937 | 9.90% |
| Greenpeace Energy [R]evolution (2015) – Advanced Energy Revolution Scenario | 4,966 | 7.35% |

# References

Abbasi, T., Abbasi, S.A. (2011). Small Hydro and the Environmental Implications of Its Extensive Utilization. *Renewable and Sustainable Energy Reviews 15*, No. 4 (May 2011): 2134-43. doi:10.1016/j.rser.2010.11.050.

AMPERE. (2014). *Ampere Project (2014).* European Union. Brussels. Retrieved from Ampere Public Database: https://tntcat.iiasa.ac.at/AMPEREDB/

Ardizzon, G., Cavazzini, G and Pavesi, G. (2014). A New Generation of Small Hydro and Pumped-Hydro Power Plants: Advances and Future Challenges. *Renewable and Sustainable Energy Reviews 31* (March 2014): 746-61. doi:10.1016/j.rser.2013.12.043.

Arias-Gaviria, J., Zwaan, B.v.d, Kober, T., Aramburo, S A. (2017). The prospects for Small Hydropower in Colombia. *Renewable Energy Vol 107 (July 2017). pp 204-214*. Retrieved from doi: 10.1016/j.renene.2017.01.054

Bajaj, J. M., Mukherjee, N., & Kulkarni, A.V. (2007). *Grid-connected Small Hydropower (SHP) Development: Regulatory Issues and Challenges*. International Conference on Small Hydropower. Kandy. (Oct.21-24, 2007). Sri Lanka.

Black & Veatch. (2012). *Cost and Performance Data for Power Generation Technologies*. Prepared for the National Renewable Energy Laboratory. Black & Veatch Holding Company. Retrieved from https://www.bv.com/docs/reports-studies/nrel-cost-report.pdf

Bloomberg New Energy Finance. (2012). *Climatescope 2012: Assessing the Climate for Climate Investigating in Latin America and the Caribbean*, 2012. Retrieved from: https://about.bnef.com/blog/climatescope-2012-assessing-the-climate-for-climate-investing-in-latin-america-and-the-caribbean/

Blyashko, Y. I. (2010). Modern Trends in the Development of Small Hydro Power around the World and in Russia. *Thermal Engineering 57, No. 11* (November 2010): *953-60*. doi:10.1134/S0040601510110078.

Bogdanov, D., Breyer, C. (2016). North-East Asian Super Grid for 100% Renewable Energy supply: Optimal Mix of Energy Technologies for Electricity, Gas and Heat Supply Options. *Energy Conversion and Management 112* (March 2016*):* 176-90. doi:10.1016/j.enconman.2016.01.019.

BP. (2014). *Statistical Review of World Energy 2014.* British Petroleum, London. Available: https://vdocuments.mx/bp-statistical-review-of-world-energy-2014.html

Criqui, P., Kouvaritakis, N. (2000). World Energy Projections to 2030. *International Journal of Global Energy Issues 14, no. 1-4 (2000): 116-136.*

Ecofys. (2018). *Energy transition within 1.5ºC.* A disruptive approach to 100% decarbonization of the global energy system by 2050. Ecofys- A Navigant Company. Retrieved from: <https://www.navigant.com/-/media/www/site/downloads/energy/2018/navigant2018energytransitionwithin15c.pdf>

EIA (n.d.). *Updated estimates of power plant capital and operating costs*. US Energy Information Administration. Washington. Table 1. Retrieved from: www.eia.gov/outlooks/capitalcost/xls/table1.xls

Elbatran, A.H., Yaakob, O.B., Yasser, M. A., Shabara, H.M. (2015). Operation, Performance and Economic Analysis of Low Head Micro-Hydropower Turbines for Rural and Remote Areas: A Review. *Renewable and Sustainable Energy Reviews 43* (March 2015): 40-50. doi:10.1016/j.rser.2014.11.045.

Equinor. (2018). *Energy Perspectives 2018, Long-term macro and market outlook.* Equinor. Retrieved from: <https://www.equinor.com/en/news/07jun2018-energy-perspectives.html>

GEF. (1992). *India: Optimizing Development of Small Hydel Resources in the Hilly Regions*. Global Environment Facility (1992). Washington. Retrieved from: https://www.thegef.org/project/optimizing-development-small-hydel-resources-hilly-areas.

Hanafi, J. & Riman, A. (2015). *Life Cycle Assessment of a Mini Hydro Power Plant in Indonesia: A Case Study in Karai River.* The 22nd CIRP Conference on Life Cycle Engineering, 29. (2015), pp. 444-449. Section 2.1. doi:10.1016/j.procir.2015.02.160

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

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

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

IEA. (2018a). *Renewables 2018.* International Energy Agency, Paris, France. Retrieved from https://www.iea.org/renewables2018/.

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

IEEJ. (2018). *IEEJ Outlook 2019 – Energy transition and a thorny oath for 3E challenges.* The Institute of Energy Economics Japan. Available at: <https://eneken.ieej.or.jp/data/8122.pdf>

IFC. (2015). Hydroelectric Power : A Guide for Developers and Investors. 2015. World Bank. Washington.

IHA. (2018). Hydropower Status Report 2018. International Hydropower Association. London.p.98

MNRE (2012). MNRE Report on Small Hydro Power, 2012. Ministry of New and Renewable Energy, Govt of India. New Delhi. Retrieved from: http://www.eaLiniclub/users/Rahul/blogs/7297.

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

IRENA. (2015). *Hydropower: Technology Brief.* International Renewable Energy Agency, Abu Dhabi. Retrieved from <https://www.irena.org/publications/2015/Feb/Hydropower>

IRENA (2016). *A Roadmap for a Renewable Energy Future.* 2016. International Renewable Energy Agency, Abu Dhabi. Retrieved from : http://www.irena.org/DocumentDownloads/Publications/lRENA\_REmap\_2016\_edition\_report.pdf.

IRENA. (2017). *Renewable Energy Statistics 2017.* International Renewable Energy Agency, Abu Dhabi IRENA. (2018). *Renewable Energy Statistics 2018.* International Renewable Energy Agency, Abu Dhabi. Retrieved on 15 November 2018 from https://www.irena.org/publications/2018/Jul/Renewable-Energy-Statistics-2018. Abu Dhabi: IRENA.

IRENA. (2018a). *Power Generation Costs in 2017.* International Renewable Energy Agency, Abu Dhabi. Retrieved on 25 November 2018 from <https://www.irena.org/publications/2018/Jan/Renewable-power-g> eneration-costs-in-2017. Abu Dhabi: IRENA.

IRENA. (2018b). *Global Energy Transformation : A Roadmap to 2050;* Retrieved on 15 November 2018 from: https://www.irena.org//media/Files/IRENA/Agency/Publication/2018/Apr/IRENA\_Report\_GET\_2018.pdf*.* Abu Dhabi: IRENA.

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

Jamasb, T., Kohler, J. (2007). *Learning Curves For Energy Technology: A Critical Assessment.* In M. Grubb(Ed), Delivering a Low Carbon Electricity System: Technologies, Economics and Policy. Retrieved from https://doi.org/10.17863/CAM.5144

Toan, K.P., Bao, N.M. Dieu, N.H. (2011). Energy Supply, Demand, and Policy in Viet Nam, with Future Projections. *Energy Policy 39, no. 11 (November 2011): 6814-26.* doi:10.1016/j.enpol.2010.03.021.

Kumar, D. and Katoch, S.S. (2015). Small Hydropower Development in Western Himalayas: Strategy for Faster Implementation. *Renewable Energy 77 (May 2015): 571-78.* doi:10.1016/j.renene.2014.12.058.

Kurup, P. R. (2018). *Analysis of Supply Chains and Advanced Manufacturing of Small Hydropower Systems.* National Renewable Energy Laboratories(NREL). 2018. Golden, Colorado.

Kusakana, K.. (2015). Feasibility Analysis of River off-Grid Hydrokinetic Systems with Pumped Hydro Storage in Rural Applications. *Energy Conversion and Management 96 (May 2015): 352-62.* doi:10.1016/j .enconman.2015 .02.089.

Manders, T. N., Hoffken, J.I. and Vleuten, E.B.A. (2016). Small-Scale Hydropower in the Netherlands: Problems and Strategies of System Builders. *Renewable and Sustainable Energy Reviews 59 (June 2016): 1493-1503.* doi:10.1016/j.rser.2015.12.100.

Mishra, M., Khare, N and Agrawal, A B. (2015). Small Hydro Power in India: Current Status and Future Perspectives. *Renewable and Sustainable Energy Reviews 51 (November 2015): 101-15.* doi:10.1016/j .rser.2015 .05.075.

MNRE. (2018). *Annual Report 2017-18.* New Delhi: Ministry of New and Renewable Energy, Govt of India.

NREL. (2018). *Annual Technology Baseline.* National Renewable Energy Laboratories(NREL). 2018 Golden: Colorado.

Paish, O. (2002). Small Hydro Power: Technology and Current Status. *Renewable and Sustainable Energy Reviews 6, no. 6 (2002): 537-556.*

Pang, M., Zhang, L., Wang, C. and Liu, G. (2015) Environmental Life Cycle Assessment of a Small Hydropower Plant in China. *The International Journal of Life Cycle Assessment 20, no. 6 (June 2015): 796-806.* doi:10.1007/s11367-015-0878-7.

Partridge, I. (2013). Renewable electricity generation in India - A learning rate analysis . *Energy Policy, Vol 60. Sept. 2013.pp- 906-915.*

Purohit, P. (2008). Small Hydro Power Projects under Clean Development Mechanism in India: A Preliminary Assessment. *Energy Policy 36, no. 6* (June 2008): 2000-2015. doi:10.1016/j.enpol.2008.02.008.

Ram M., Bogdanov, D., Aghahosseiniu, A., Oyewo, A.S., Gulagi, A., Child, M., Fell, H.K., Breyer, C. (2017). Global Energy System based on 100% Renewable Energy – Power Sector., Study by Lappeenranta University of Technology and Energy Watch Group. Lappeenranta, Berlin, November 2017.

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

REN21. (2017). *Renewables 2017 Global Status Report.* Renewable Energy Policy Network Secretariat. Paris.

REN21. (2018). *Renewables 2018: Global Status Report.* Renewable Energy Policy Network Secretariat. Paris.

Roque, A., Sousa, D.M., Casimiro, C. and , E (2010). *Technical and Economic Analysis of a Micro Hydro Plant in 2014; a Case Study, 1-6. IEEE, 2010.* doi:10.1109/EEM.2010.5558735.

Sachdev, H. S., Akella, A.K. and Kumar, N. (2015). Analysis and Evaluation of Small Hydropower Plants: A Bibliographical Survey. *Renewable and Sustainable Energy Reviews 51* (November 2015): 1013-22. doi:10.1016/j.rser.2015.06.065.

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

Svensson, B. S. (2000). Hydropower and Instream Flow Requirements for Fish in Sweden*. Fisheries Management and Ecology 7, no. 1-2* (2000): 145-155.

Teske, S. M. (2015). *100% Renewable* Energy *For All: energy [r]evolution - A sustainable World Energy Outlook 2015.* Hamburg: Greenpeace.

Tully, S. (2006). The Human Right to Access Electricity. *The Electricity Journal 19, no. 3 (April 2006): 30-39.* doi:10.1016/j.tej.2006.02.003.

Turconi, R., Boldrin, A., & Astrup, T. F. (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renewable and Sustainable Energy Reviews, 28, 555- 565.* doi: 10.1016/j.rser.2013.08.013

UNIDO. (2013). *World Small Hydro Report 2013.* Vienna: UNIDO and International Small Hydro Centre.

UNIDO. (2016). *World Small Hydropower Development Report 2016.* Vienna: UNIDO.

VanZwieten, J. H., McAnally, W., Ahmad,J., Davis, T, Martin, J. Bevelhimer, M.S., Cribbs, A, Lippert, R., Hudon, T. and Trudeau, M. (2014). "In-Stream Hydrokinetic Power: Review and Appraisal." *Journal of Energy Engineering 141, no. 3 (September 2015): 4014024*. doi:10.1061/(ASCE)EY.1943-7897.0000197.

Vermaak, H. J., Kusakana,K., and Koko, S.P. (2014). Status of Micro-Hydrokinetic River Technology in Rural Applications: A Review of Literature. *Renewable and Sustainable Energy Reviews 29* (January 2014): 625-33. doi:10.1016/j.rser.2013.08.066.

Vougioukli, A.Z., Eleni, D. & Dimitrios, G. (2017). Financial Appraisal of Small Hydro-Power Considering the Cradle-to-Grave Environmental Cost: A Case from Greece. (I. Nicolae, Ed.) *Energies, 10(4).* doi:10.3390/en10040430

Wang, H., Chen, Y. Liu, Z. and Zhu, D. (2016) Effects of the 'Run-of-River' Hydro Scheme on Macroinvertebrate Communities and Habitat Conditions in a Mountain River of Northeastern China. *Water 8, no. 2 (January 21, 2016): 31.* doi:10.3390/w8010031.

Winkler, H. H. (2009). Technology learning for renewable energy: Implications for South Africa's long-term mitigation scenarios. *Energy Policy, 37(11), 4987-4996.* doi: 10.1016/j.enpol.2009.06.062

World Bank. (2012). *Data on Small Hydro Projects - Renewable Energy Database, 2012.* http://www.doingbusiness.org/re/snapshots/technology/small-hydro.

Yuce, M. I., Muratoglu, A. (2015). Hydrokinetic Energy Conversion Systems: A Technology Status Review. *Renewable and Sustainable Energy Reviews 43 (March 2015): 72-82.* doi:10.1016/j.rser.2014.10.037.

Zema, D. A., Nicotra, A., Tamburino, V., Zimbone. S.M. (2016). A Simple Method to Evaluate the Technical and Economic Feasibility of Micro Hydro Power Plants in Existing Irrigation Systems. *Renewable Energy 85 (January 2016): 498-506. doi:10.1016/j.renene.2015.06.066.*

Zhang, J., Xu, L. and Li, X. (2015). Review on the Externalities of Hydropower: A Comparison between Large and Small Hydropower Projects in Tibet Based on the CO2 Equivalent. *Renewable and Sustainable Energy Reviews 50 (*October 2015): 176-85. doi:10.1016/j.rser.2015.04.150.

# Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1. Gestation period means the time it takes to actually set up the project once the investment decision is made.  [↑](#footnote-ref-2)
2. Scalability means how easily can we upgrade the size of the plant by adding more modules or turbines. [↑](#footnote-ref-3)
3. 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-4)
4. 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-5)
5. 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-6)
6. All monetary values are presented in US$2014 [↑](#footnote-ref-7)
7. Accounts for total hydro systems electricity generation. [↑](#footnote-ref-8)