**Technical assessment for**

**Nuclear Power**

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Table of Contents

[List of Figures 4](#_Toc19323132)

[List of Tables 4](#_Toc19323133)

[Acronyms and Symbols Used 5](#_Toc19323134)

[Executive Summary 7](#_Toc19323135)

[1 Literature Review 8](#_Toc19323136)

[1.1. State of Nuclear Energy 8](#_Toc19323137)

[1.2. Adoption Path 8](#_Toc19323138)

[1.2.1 Current Adoption 8](#_Toc19323139)

[1.2.2 Trends to Accelerate Adoption and Barriers 10](#_Toc19323140)

[1.3 Advantages and Disadvantages of Nuclear Power 12](#_Toc19323141)

[1.3.1 Similar Solutions 12](#_Toc19323142)

[1.3.2 Arguments for Adoption 12](#_Toc19323143)

[1.3.3 Additional Benefits and Burdens 12](#_Toc19323144)

[2 Methodology 15](#_Toc19323145)

[2.1 Introduction 15](#_Toc19323146)

[2.2 Data Sources 16](#_Toc19323147)

[2.3 Total Addressable Market 18](#_Toc19323148)

[2.4 Adoption Scenarios 19](#_Toc19323149)

[2.4.1 Reference Case / Current Adoption 19](#_Toc19323150)

[2.4.2 Project Drawdown Scenarios 19](#_Toc19323151)

[2.5 Inputs 20](#_Toc19323152)

[2.5.1 Climate Inputs 20](#_Toc19323153)

[2.5.2 Financial Inputs 21](#_Toc19323154)

[2.5.3 Technical Inputs 23](#_Toc19323155)

[2.6 Assumptions 24](#_Toc19323156)

[2.6 Integration 24](#_Toc19323157)

[3 Results 26](#_Toc19323158)

[3.1 Adoption 26](#_Toc19323159)

[3.2 Climate Impacts 27](#_Toc19323160)

[3.3 Financial Impacts 29](#_Toc19323161)

[4 Discussion 31](#_Toc19323162)

[4.1 Limitations 31](#_Toc19323163)

[4.2 Benchmarks 31](#_Toc19323164)

[5 References 33](#_Toc19323165)

[6 Glossary 36](#_Toc19323166)

# List of Figures

[Figure 3.1 World Annual Adoption 2015-2060 27](#_Toc44543350)

[Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction (2015-2060) 29](#_Toc44543351)

# List of Tables

[Table 1.1 U.S. Average Levelized Costs for Dispatchable and Non-Dispatchable Technologies (EIA, 2015) 11](#_Toc19323115)

[Table 1.2 Trends that accelerate and decelerate nuclear power 11](#_Toc19323116)

[Table 1.3 Estimated Uranium Resources (Price and Blaise, 2002) 13](#_Toc19323117)

[Table 1.4 Summary of Advantages and Disadvantages of Nuclear Power 14](#_Toc19323118)

[Table 2.1 Climate Inputs 21](#_Toc19323119)

[Table 2.2 Financial Inputs for Conventional Technologies 22](#_Toc19323120)

[Table 2.3 Financial Inputs for Solution 22](#_Toc19323121)

[Table 2.4 Technical Inputs Conventional Technologies 23](#_Toc19323122)

[Table 2.5 Technical Inputs Solution 23](#_Toc19323123)

[Table 3.1 World Adoption of the Solution 26](#_Toc19323124)

[Table 3.2 Climate Impacts 27](#_Toc19323125)

[Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq 28](#_Toc19323126)

[Table 3.4 Financial Impacts 29](#_Toc19323127)

[Table 4.1 Benchmarks 32](#_Toc19323128)

# Acronyms and Symbols Used

* 2D - 2 degrees scenario
* B2D – Beyond 2 degrees scenario
* BOP – Balance-of-plant
* BWR - Boiling water reactor
* CO2 – Carbon dioxide
* DS – Degree Scenario
* EAR - Estimated additional resources
* ETP – Energy Technology Perspectives
* EU – European Union
* EV – Electric Vehicle
* EWG - Energy Watch Group
* FBR - Fast breeder reactor
* GCR - Gas-cooled reactors
* GHG – Greenhouse Gases
* Gt – Gigatons
* GW - Gigawatts
* HTGR - high temperature gas-cooled reactor
* HWR - Heavy-water-moderated reactor
* IAEA – International Atomic Energy Agency
* IEA – International Energy Agency
* IEEJ – The Institute of Energy Economics, Japan
* IPCC – Intergovernmental Panel for Climate Change
* IRENA – International Renewable Energy Agency
* LCA – Life Cycle Assessment
* LCOE – Levelized costs of electricity
* LEU - Low-enriched uranium
* LUT - Lappeenranta University of Technology
* LWGR - Light-water-cooled graphite moderated reactor
* LWR - light-water reactor
* MOX – Mixed Oxides
* NEA – Nuclear Energy Agency
* NPP – Nuclear Power Plants
* O&M – Operation and Maintenance
* OECD – The Organisation for Economic Co-operation and Development
* PPM - parts per million
* PTGR - Pressure tube graphite reactor
* PWR - Pressurized water reactor
* PWR - pressurized water reactors
* R&D – Research and Development
* RAR - Reasonable assured resources
* REF – Reference Scenario
* RES – Renewable Energy Sources
* RRS - Reduction and Replacement Solutions Model
* SDS – Sustainable Development Scenario
* SR – Speculative Resources
* TAM - Total Addressable Market
* TWh - Terawatt-Hours
* US – United States
* USD – United States Dollar
* VRES - Variable Renewable Energy Sources
* WEO – World Energy Outlook
* WI – Nuclear Island

# Executive Summary

Project Drawdown defines nuclear as: the electricity generation from nuclear fission in the form of Uranium 235 as used in pressurized water reactors, a type of light-water reactor using low-enriched uranium fuel. This solution replaces conventional electricity-generating technologies such as coal, oil, and natural gas power plants. Commercialized civil nuclear energy captures the energy released by the splitting of atoms in radioactive elements. This energy can be extremely powerful and resource-efficient: 1 kilogram of uranium-235 contains two to three million times the energy equivalent of 1 kilogram of oil or coal (ENS, 2016). During nuclear fission in the reactor core, heat is produced; this heat is used to boil water into steam; the steam then turns turbine blades that drive generators to make electricity.

This analysis models the adoption of nuclear fission as used in pressurized water reactors, a type of light-water reactor using low-enriched uranium fuel, the most prevalent form of nuclear energy in 2016. Advanced reactors such as thorium-based reactors, gas-cooled reactors, pebble bed reactors, and other technologies in the pre-commercialization phases are out of the scope of this research. The total addressable market for nuclear electricity generation is based on projected global electricity generation in terawatt-hours from 2020-2050, with current adoption estimated at around 12.2% of generation (i.e. 2,752 terawatt-hours). Impacts of increased adoption of nuclear from 2020-2050 were generated based on three growth scenarios, which were assessed in comparison to a Reference Scenario where the solution’s market share was fixed at the current levels. *Plausible Scenario* is based on the evaluation of six climate optimistic scenarios and ambitious solution adoption scenarios from IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; Equinor (2018) Renewal Scenario; Grantham Institute and Carbon Tracker (2017) with the strong mitigation policy scenario, with Original technology costs and Medium energy demand; and IEEJ (2018) Advanced Tech Scenario; using a medium growth trajectory. In this scenario nuclear captures 13.4% of the electricity generation market share in 2050 (i.e. 6,093 terawatt-hours). *Drawdown Scenario* follows the same adoption trajectory as the *Plausible scenario.* With the target of 100% electricity generation from RES in 2050, Optimum Scenario shows a reduction to zero by 2050 of nuclear power use. This scenario builds upon the combined analysis of the results of three 100% RES scenarios of electricity generation by 2050, being Greenpeace (2015) Advanced Energy [R]evolution Scenario; Ram *et al.* (2019) scenario and Ecofys (2018) 1.5ºC scenario.

Compared to the Reference Scenario, the financial results for the Plausible Scenario of adoption show marginal first costs of US$192 billion from 2020-50, and near US$159 billion in savings over the same period. Under the Plausible Scenario, the adoption of nuclear for electricity generation could avoid 3.25 gigatons of carbon dioxide-equivalent greenhouse gas emissions from 2020-2050. Drawdown Scenario projects that nuclear represents 8.6% of the TAM in 2050 with the same impact as the Plausible Scenario (i.e. 2.9 gigatons of carbon dioxide-equivalent greenhouse gas emissions). Due to the phasing out of all nuclear powerplants by 2050, the Optimum Scenarios unfolds negative results for total emissions reductions of -55.4 gigatons when compared to the REF scenario.

The adoption of nuclear power plants depends on a number of factors. Trends that may accelerate its adoption include: the public acceptance of nuclear power as a climate change abatement and job creation strategy; the commercialization of technologies that produce less radioactive waste; government support (subsidies, loan guarantees, etc.) of nuclear power; and a carbon tax. Trends that may decelerate the adoption of nuclear power plants include: public disapproval of nuclear power, nuclear incidents and accidents, lack of nuclear power skills training, and cost overruns and delays on the construction. Advantages of increasing nuclear energy adoption include: the zero-carbon nature of generation, provision of baseload capability, a high capacity factor, and the ability to use nuclear’s waste heat to power other systems. The disadvantages of increasing nuclear energy adoption include legacy waste and the public perception of risk that leads to a high cost of capital for new builds.

# Literature Review

## State of Nuclear Energy

The scope of the Nuclear Energy Drawdown solution is nuclear fission in the form of Uranium 235 as used in pressurized water reactors (PWRs), a type of light-water reactor (LWRs), using low-enriched uranium (LEU) fuel, the most prevalent form of nuclear energy. Out of scope are advanced reactors such as thorium-based reactors, gas-cooled reactors, pebble bed reactors, and other technologies in the pre-commercialization phases.

Commercialized civil nuclear energy, based on the fission of uranium-235, captures the energy during the splitting of atoms in radioactive elements. This energy can be extremely powerful and resource efficient—1 kilogram of uranium-235 contains two to three million times the energy equivalent of 1 kg of oil or 1 kg of coal (ENS, 2016).

In nuclear fission, atoms release energy when they split apart to form smaller atoms. The atoms originate from fuel—the most common fuel source being uranium. Uranium is mined from deposits around the world, with the largest deposits of uranium located in Canada, Kazakhstan, Australia, Russia and Niger. Uranium is chemically processed, formed into ceramic pellets, stacked end-to-end in metal fuel rods, assembled into a bundle (a bundle contains sometimes hundreds of fuel rods), and inserted into a reactor core. During nuclear fission in the reactor core, heat is produced; this heat is used to boil water into steam; the steam then turns turbine blades that drive generators to make electricity.

## Adoption Path

### Current Adoption

Annually, there are about 2.8 trillion kWh of electricity generated globally from nuclear power (Fetter, 2009), representing about 15% of the world’s electricity. Since the Fukushima accident in March 2011, nuclear power has decreased to about 11% of the world electricity market share and evolves as Japan restarts its nuclear reactors.

Nuclear power is the largest source of low-carbon electricity in OECD countries and second at a global level. As a point of comparison, as of 2019, there are 60 operating nuclear power plants in the United States, representing about 20% of the USA’s electricity footprint, and 58 operating nuclear power plants in France, representing 75-80% of France’s electricity. As of 2016, 30 countries worldwide are operating 450 nuclear reactors for electricity generation and 60 new nuclear plants are under construction in 15 countries (IAEA, 2019).

This technology is a mature one, with the engineering, design, construction, operation, and decommissioning of LWRs very well understood. In recent years, however, the construction of Generation III/III+ reactors have been met with significant delays and cost overruns. For example, as of October 2016, the Olkiluoto 3 LWR in Finland is 10 years behind schedule and €5 billion over budget. Generation III reactors are characterized by standardized design, high availability and a long operating life of 60 years, resistance to an aircraft impact, higher burn-up to use fuel more fully and reduce waste, and greater use of burnable absorbers to extend fuel life (WNA, 2016). Also, as of 2015, The US-based Vogtle NPP expansion costs were originally estimated at $6.1 billion, but have grown to $7.4 billion with an operating date pushed back by two years (Overtun, 2015).

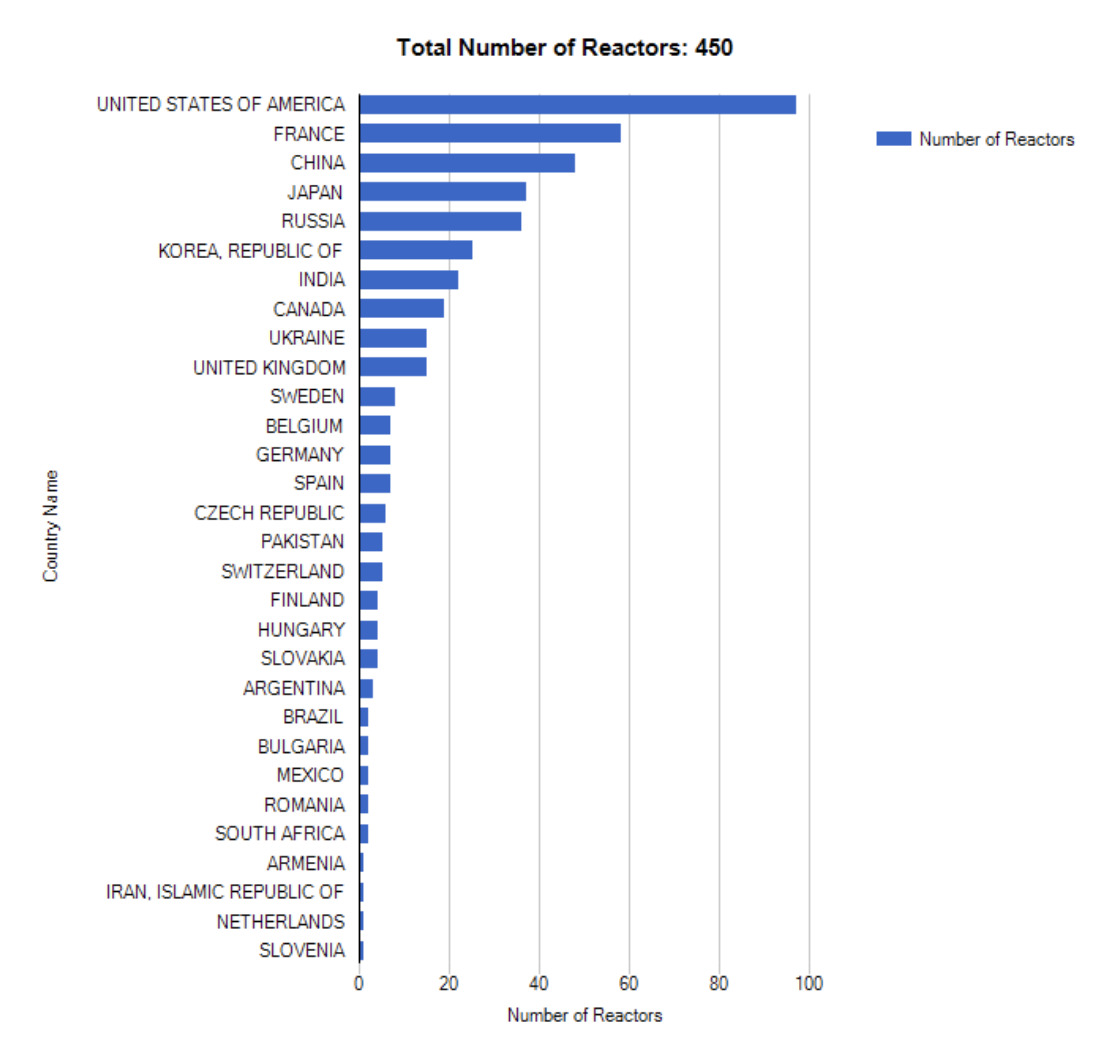


Figure 1.1 - Number of Nuclear Power Reactors Operating Worldwide by Country (Source: IAEA PRIS, 2019)

### Trends to Accelerate Adoption and Barriers

To expand NPPs, a significant expansion of human resources, increased public confidence in the technology, and improved economic feasibility for each new project would be needed. On average, nuclear plants directly employ 400-700 people, and a single unit may directly employ as many as 1,000 people (NRC, 2013). The nuclear industry thus often encompasses a large employment footprint where it operates. Nuclear power requires expertise in a variety of science and technology fields such as radioprotection, nuclear physics, most engineering disciplines, and instrumentation and control. These skills and competencies take time and training to build. The total potential workforce loss from retirement and other attrition in the nuclear power field could be as much as 48% in a 5-year time horizon, presenting unique worker shortfall challenges for the maintenance and expansion of nuclear energy (NRC, 2013).

The expansion of nuclear power requires the right to operate in the eyes of the public. Nuclear power has long suffered from a bad public image, partly due to public misunderstanding of the differences between atomic weapons and civil nuclear energy, proliferation concerns, and highly dramatized plant incidents. If nuclear power is to have a future, increased awareness and understanding by the public coupled with public acceptance will be necessary.

Finally, the economics of nuclear power compared to other low-carbon sources of energy must be favorable in order to maintain and expand the existing fleet of reactors. The economics include not only the cost to construct, operate, and decommission a NPP, but also to remove, treat and permanently dispose of or store spent nuclear fuel from the plants. The ability of nuclear power projects to stay within budget and be delivered on time is an important component of the economics; there have been significant cost overruns in recent years, especially for reactors constructed in developed economies. Levelized cost of electricity (LCOE) is the per-kWh cost of building and operating a generating plant over an assumed financial life and duty cycle; inputs include capital costs, fuel costs, fixed and variable operations and maintenance costs, financing costs, and an assumed utilization rate for each plant type (EIA, 2013). Nuclear power becomes an attractive option when using the LCOE metric (Table 1.1). Table 1.2. provides a summary of key factors that might accelerate or be a barrier to increase Nuclear adoption.

Table 1.1 U.S. Average Levelized Costs for Dispatchable and Non-Dispatchable Technologies (EIA, 2015)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **U.S. Average Levelized Costs (2013 $/MWh) for Plants Entering Service in 2020** | | | | | |
| **Plant Type** | **Capacity Factor (%)** | **Levelized Capital Cost** | **Fixed O&M** | **Variable O&M (including fuel)** | **Transmission Investment** | **Total System LCOE** |
| **Dispatchable Technologies** | | | | | | |
| Conventional Coal | 85 | 60.4 | 4.2 | 29.4 | 1.2 | 95.1 |
| Advanced Coal | 85 | 76.9 | 6.9 | 30.7 | 1.2 | 115.7 |
| Natural Gas-fired Advanced Combined Cycle | 87 | 15.9 | 2.0 | 53.6 | 1.2 | 72.6 |
| Advanced Nuclear | 90 | 70.1 | 11.8 | 12.2 | 1.1 | 95.2 |
| Geothermal | 92 | 34.1 | 12.3 | 0.0 | 1.4 | 47.8 |
| Biomass | 83 | 47.1 | 14.5 | 37.6 | 1.2 | 100.5 |
| **Dispatchable Technologies** | | | | | | |
| Onshore Wind | 36 | 57.7 | 12.8 | 0.0 | 3.1 | 73.6 |
| Offshore Wind | 38 | 168.6 | 22.5 | 0.0 | 5.8 | 196.9 |
| Solar PV | 25 | 109.8 | 11.4 | 0.0 | 4.1 | 125.3 |
| Solar Thermal | 20 | 191.6 | 42.1 | 0.0 | 6.0 | 239.7 |
| Hydroelectric | 54 | 80.7 | 3.9 | 7.0 | 2.0 | 83.5 |

Table 1.2 Trends that accelerate and decelerate nuclear power

|  |  |
| --- | --- |
| **Trends that Accelerate Adoption of NPP** | **Trends that Decelerate Adoption of NPP** |
| * Public acceptance of nuclear power as a climate change abatement and job creation strategy | * Public disapproval of nuclear power |
| * Commercialization of technologies that produce less radioactive waste | * Nuclear accidents |
| * Government support (subsidies, loan guarantees, etc.) of nuclear power | * Lack of nuclear power skills training |
| * Carbon tax | * Cost overruns and delays of NPP construction |

## Advantages and Disadvantages of Nuclear Power

### Similar Solutions

Due to the specific use of Uranium as input and the particularities of nuclear power, it is considered herein that there are no similar solutions in the electricity generation sector.

### Arguments for Adoption

The main advantages of nuclear energy are two-fold: (1) there are no greenhouse gas emissions while operating and (2) nuclear power plants are non-intermittent zero-emission sources of baseload power. In a greenhouse gas constrained world, it is critical to produce electricity and heat without emitting additional greenhouse gases. Nuclear reactors do not produce carbon dioxide or other air pollutants during operation, making nuclear reactors an attractive option from a climate change perspective. In addition, nuclear reactors provide this zero-carbon energy continuously—without dependence on the unpredictability of the wind or the time-limited nature of the sun. As intermittent sources are connected to grids without adequate storage capacity, it is critical to have a base load energy source that can compensate. Most base load energy options, however, are carbon-emitting fossil fuels such as coal and gas. Renewable energy base load options, namely hydropower, biomass and geothermal energy, are mostly restricted to certain geographic locations to make them economically viable.

An additional advantage of nuclear power plants is that they produce both waste heat and steam. This waste heat can be, and for some reactors is, used for district heating and to power other industrial operations (such as desalination plants). Nuclear reactors are very reliable and provide baseload power over 90% of the time. This high capacity factor is one of the primary efficiency benefits to nuclear energy over other base load sources.

### Additional Benefits and Burdens

The primary disadvantages of nuclear power are two-fold: (1) the currently commercialized technology of nuclear power plants creates legacy waste and (2) perceptions of nuclear risk and safety make the cost of capital for the construction of new power plants burdensomely high.

One of the main critiques of nuclear power is that in its current form, radioactive waste such as uranium mill tailings and spent (or used) reactor fuel is created. The spent fuel waste can be toxic and hazardous, and remain so during their radioactive lifetime that can last thousands of years. Some solutions exist to reduce the amount of waste and create a closed loop cycle where nuclear fuel is recycled. In France, for example, spent fuel is reprocessed so that it can be reused and remade into fuel, rods, and assemblies. This recycled fuel is called MOX—for mixed oxides. Since the 1970s, 41 reactors have been loaded with MOX fuel assemblies, representing about 10% of the world’s LWRs: 36 in Europe (21 in France, 10 in Germany, 3 in Switzerland and 2 in Belgium), 1 is in the United States and 4 are in Japan (AREVA, 2016). Other forms of nuclear power in the research and development (R&D) phase, including fusion, would significantly reduce the need for waste disposal sites if these new forms were commercially deployed.

There were no direct radiation-induced casualties caused from the Fukushima Daiichi nuclear power plant (NPP) accident, though it raised concerns over the safety of NPPs and provoked a decrease in confidence by the public, changing energy policies in some countries such as Germany (OECD/IEA/Nuclear Energy Agency, 2015).

Other points of contention concerning nuclear power are the abundance of uranium and life cycle emissions. There is some debate as to how long uranium can be found, with some sources pointing to 200 years while others claim that it is indefinite as we learn to extract uranium from seawater. The OECD NEA has estimated the uranium resources by known conventional resources, undiscovered conventional resources, secondary sources, and unconventional resources.

Table 1.3 Estimated Uranium Resources (Price and Blaise, 2002)

|  |  |
| --- | --- |
| Resource type | Estimate (1,000 t) |
| *Known conventional resources:* | |
| Reasonable assured resources (RAR) | 2,850 |
| Estimated additional resources cat. I (EAR-I) | 1,080 |
| *Undiscovered conventional resources:* | |
| Estimated additional resources cat. II (EAR-II) | 2,330 |
| Speculative resources (SR) | 9,940 |
| *Secondary sources:* | |
| Commercial inventories | 220 |
| Surplus defense inventories | 250 |
| Re-enrichment | 440 |
| *Unconventional resources:* | |
| In phosphates | 22,000 |
| In seawater | 4,000,000 |
| TOTAL | **4,039,110** |

Carbon emissions are emitted during mining uranium, and to manufacture metal and concrete used to build a plant. However, lifecycle carbon emissions are likewise associated with other low-carbon energy sources such as photovoltaic panels and wind turbines.

Table 1.4 Summary of Advantages and Disadvantages of Nuclear Power

|  |  |
| --- | --- |
| Advantages | Disadvantages |
| * Zero carbon | * Legacy waste |
| * Non-intermittent source of low carbon energy (baseload capability) | * Public perception of risk (leads to high cost of capital for new builds) |
| * High capacity factor (high reliability, efficiency) |  |
| * Waste heat can power other important functions such as district heating and desalination |  |
| Points of Contention: | |
| * Availability of nuclear fuel as a renewable fuel (uranium deposits, ability to commercialize thorium reactors, etc.) | |
| * Life cycle emissions from mining and refining uranium to building plants | |

# Methodology

## Introduction

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

For this solution, the approach was to analyze the impacts of increased adoption of nuclear powerplants. The models used for this analysis construct both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for nuclear energy. Following project Drawdown methodological assumption (further description available on the Drawdown RRS Model Framework and Guide), in order to grasp the total impact of an increased adoption of the solution during the assessed time frame; the REF scenario assumes future adoption of nuclear units remains fixed at the current year (i.e. 2018) percentage of Total Addressable Market (TAM), estimated at 12.2 percent (2,752 terawatt-hours) 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 nuclear. 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 nuclear energy, as well as the contribution of these adoptions, can make to annual and cumulative emissions reduction.

## Data Sources

This section presents key data sources utilized in the model to evaluate the adoption of nuclear energy technologies. Data inputs for the model come from a variety of sources, primarily from peer-reviewed publications and from institutional reports. For all variable inputs, it was done a variable meta-analysis of existing literature to create low, high, and mean estimates. For each solution variable, it is conducted a sensitivity analysis of, on average, 13 data points reported in the literature and in some cases as many as 50. This allows calculating robust and reliable inputs for the financial, technological and climate analyses that represent both optimistic and conservative estimates for the future costs and benefits of adopting this solution.

For the global adoption scenarios, it were selected eight sources with fifteen (15) scenarios including 2018 IEA World Energy Outlook (Current Policy, New Policy, and Sustainable Development scenarios); 2017 IEA Energy Technology Perspectives (Reference Technology, 2 Degrees, and Beyond 2 Degrees scenarios); 2018 Equinor’s Energy Perspectives (Rivalry, Reform, and Renewal scenarios); 2017 Grantham/Carbon Tracker Report (moderate fossil fuel intensive or NDC\_PE\_EV\_Medium, and least fossil fuel intensive or Strong\_PV\_EV\_Medium); 2019 IEEJ Outlook (Reference and Advanced Technology scenarios); RAM et al (2018) 100% Renewable Energy scenario; and Ecofys (2018) 1.5ºC scenario.

Several lifecycle assessments (LCAs) have been conducted for nuclear power technologies across the globe over the last 30 years (*e.g.* NREL, 2012; Kadiyala, et. al., 2016; Mac Kinnon et al. 2018; IAEA, 2018). LCAs determine the environmental impacts of products and technologies throughout their full lifetime, from raw material extraction and processing; to manufacturing and distribution; to use and maintenance; to disposal or recycling. LCAs include estimates of total greenhouse gas (GHG) emissions and other environmental impacts and resources used (*e.g.* water and land use, air pollutants emissions). Data. Inputs were considered or several types iof nuclear reactors as: Boiling water reactor (BWR); Pressurized water reactor (PWR); Heavy-water-moderated reactor (HWR); Gas-cooled reactors (GCR); Light-water-cooled graphite moderated reactor (LWGR)/pressure tube graphite reactor (PTGR); Fast breeder reactor (FBR); high temperature gas-cooled reactor (HTGR); modular HTGR (usually called GT-MHR).

For the nuclear energy solution, the values for indirect CO2 emissions range from 0.8 g-CO2eq/kWh to 220 g-CO2eq/kWh. This large differential is due mostly to differences in enrichment, production, and operation, with a large carbon footprint difference in diffusion enrichment compared to centrifuge enrichment. The energy requirement for gaseous centrifuge enrichment ranges from 40-100 kWh/SWU, whereas gaseous diffusion requires 2400-3000 kWh/SWU (Fthenakisa, 2007).

There are three types of capital costs for a nuclear power plant: nuclear island (NI), the conventional island (CI), sometimes known as the turbine island, and the balance-of-plant (BOP). The key components of the NI are the reactor, the reactor coolant pumps, the pressurizer, and the steam generators. The key components of the CI are the steam turbine, generator, condenser, condensate-feedwater system, moisture separator reheater, cooling system, and instrumentation and control system. The BOP are the remaining systems.

Recent capital cost estimates from several data sources, presenting data for all of the regions contained in this analysis, were analyzed to determine the average capital cost of NPP installations (e.g. IEA, 2014; IPCC, 2014; IAEA, 2013). It is acknowledged that capital costs can vary significantly by region, but exhaustive regional data were not available to calculate an average cost weighted by installation size. Available estimates were concentrated in OECD countries and China, reflecting the preponderance of present-day nuclear power installations.

Cost estimates for fixed operation and maintenance (O&M) of NPPs were collected from a variety of sources (IPCC, 2014); (EIA, 2013), and these estimates were used to calculate total operating costs of NPP adoption, which, combined with capital costs for installation, represent the total financial costs of adopting nuclear energy in the PD scenarios. Fixed operation and maintenance costs include expenses such as day-to-day preventative and corrective maintenance, labor costs, asset and site management, and maintaining health and safety.

In order to calculate the total financial costs and benefits of PD scenarios adoptions, it was analyzed data for several additional variables, including average annual use, average fuel price, and average plant efficiency. 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.

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.

Data was collected from a range of different sources (EIA, 2015; IEA, 2016; IAEA, 2003) that represent most of the regions contained in the analysis. Some of the PD regions are absent, however, because data for these specific regions were not readily available.

Rubin et al. summarize learning rates (i.e. fractional reduction in cost per doubling of cumulative capacity or production) for wide variety of electricity generation technologies. However, the paper has limited information on nuclear power learning rates, and none before 1972 or after 1996. Lang (2017) states that if “*the rate of commercial nuclear deployment in the late-1960s to 1970s been maintained to the present day, nuclear power could now be around 10 percent of its current cost and according to him could have substituted for 69,000 to 186,000 TWh of coal and gas generation—thereby avoiding up to 9.5 million deaths and 174 Gt CO2 emissions. Learning rates and deployment rates changed in the late-1960s and 1970s from rapidly falling costs and accelerating deployment to rapidly rising costs and stalled deployment (Lang, 2017). If pre reversal learning rates were to be considered, they could range from 7% in India to 35% in Japan. Pre reversal indicates the period before stalled deployment*”.

## 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, 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, adoption is fixed at the current adoption[[1]](#footnote-1) (in percent) of the market. Historical data of nuclear energy electricity generation until 2017 was retrieved from World Bank, 2018 value was estimated from historical values trendline. The assumption on this scenario is that current percentage of total electricity generation (TWh) provided by nuclear power is constant throughout the study period to 2050. As the market grows, the total number of nuclear powerplants adopted grows equally to maintain the percent adoption at its starting value in 2018. It is acknowledged that this, in reality, may not be a “business as usual” considering changes taking place worldwide, but it allows measurement of the impact of recent and even more aggressive policies on greenhouse gas emissions.

### Project Drawdown Scenarios

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

#### Plausible Scenario

This scenario represents an incremental and plausible growth of renewable energy solutions as well and transition solutions as nuclear, 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 nuclear power, this scenario is based on the evaluation of yearly averages of six climate optimistic and adoption scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; Equinor (2018) Renewal Scenario; Grantham Institute and Carbon Tracker (2017) with the strong mitigation policy scenario, with Original technology costs and Medium energy demand; and IEEJ (2018) Advanced Tech Scenario; using a medium growth trajectory.

#### Drawdown Scenario

This scenario is optimized to reach drawdown by 2050 using more ambitious projections from existing sources. The scenario projects a 100% adoption of non-fossil fuel-based technologies in 2050; mainly RES but also includes several technologies that are considered transitional solutions (as nuclear energy) (See section 6). Nuclear power in this scenario, follows the same data sources and adoption trajectory as the Plausible Scenario. These scenarios represent very ambitious pathway towards a fully decarbonized energy system in 2050.

#### Optimum Scenario

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

## Inputs

### Climate Inputs

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

Nuclear power do not have direct emissions related to combustion of fuels to be accounted on the GHG emissions impact calculations. Project Drawdown modeling considers the analysis of indirect emissions related to the different factors that contribute to an LCA for nuclear. In modeling the lifecycle emissions of nuclear power adoption in the scenarios, it is used a fixed value (t CO2-eq per TWh) considering information from several studies, rather than a decreasing one due to the difficulty of projecting future grid-tied emissions on a regional basis. The climate results presented herein will thus be more conservative than would be the case if it was assumed a decreasing average lifecycle emissions value for nuclear.

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

Table 2.1 Climate Inputs

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Indirect CO2 Emissions (Solution) | *t CO2-eq/TWh* | 800 – 45,196 | 18,459 | 52 | 15 |

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[[2]](#footnote-2).

### Financial Inputs

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

For the solution (nuclear), 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.

The financial inputs used in the model consider an average installation cost of US$8,331 per kilowatt with a learning rate of 2% similar to the input used for conventional technologies. Annual use of nuclear power is the highest compared to all electricity generating technologies. An average capacity factor of 82 percent is used for nuclear, compared to 57 percent for conventional technologies (*i.e.* coal, natural gas, and oil power plants). Variable operation and maintenance costs of US$0.016 per kilowatt-hour, and of US$108.8 per kilowatt for fixed costs are considered for nuclear, compared to US$0.005 per kilowatt-hour and US$34.7 per kilowatt for the conventional technologies (Tables 2.2. and 2.3).

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

Table 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 | 34.65 | 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* | 5,843 – 10,818 | 8,331 | 13 | 7 |
| Fixed Operation and Maintenance Costs (Solution) | *US$2014/kW* | 61.56 – 155.94 | 108.75 | 8 | 5 |
| Variable Operation and Maintenance Costs (Solution) | *US$2014/kWh* | 0.01 – 0.032 | 0.016 | 12 | 8 |
| Learning Rate Factor (Solution) | % | 7% - 35% | 2% | 7 | 1 |
| Uranium Prices | *US$2014/kWh* | 0.003 – 0.006 | 0.0045 | 7 | 6 |

Note: A conservative estimate was considered for nuclear power learning rate since adoption have been fairly stable in the last decades and studies (e.g. Lang et al., 2017) portray pre reversal rates.

### Technical Inputs

In order to characterize wind onshore technologies, several technical inputs are considered in the RRS as capacity factors and lifetime (Table 2.4).

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* | 301,900 – 435,235 | 368,568 | 8 | 7 |
| Average Annual Use (Solution) | *hours* | 6,550-7,833 | 7,192 | 23 | 8 |

## 2.6 Assumptions

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

1. The results from the different sources are depicted at a 5 year or 10 years’ basis and it were needed yearly, therefore data interpolation was made using the best-fit trends (*i.e.* generally 3rd polynomial but 2nd polynomial or S curve were also used).
2. Nuclear power plants in this report are restricted to fission-based reactors, mostly pressurized water reactors that use uranium as the fuel. Generation 4 nuclear reactors are excluded (pebble bed, thorium based reactors, small modular reactors, etc.).
3. Global average figures are used as model input values for the analysis for both nuclear reactors and conventional sources across a number of different regions and installation sizes.
4. Costs (or savings) for nuclear power plants are incurred by (or accrue to) the owner of the project, whether this is a developer or the utility itself.
5. All capital and operating costs (or savings) are calculated on an annual basis and then aggregated into one total at the end of the 30-year modeling period.
6. While technology costs tend to decrease over time as technology matures, following the standard equation for learning rates, PWR type of NPP that is the main focus of this solution is considered very mature, with a learning rate close to 0%. 2% LR was adopted in the nuclear RRS model, aligned with the input used for conventional technologies which are also very mature.

## Integration

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

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

Through the process of integrating nuclear energy 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.

# Results

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

## Adoption

Comparing the results from the three modeled scenarios to the Reference Scenario allow estimating the climate and financial impacts of increased adoption of nuclear systems. The *Plausible Scenario (PDS1)* projects 13.4 percent of total electricity generation worldwide coming from nuclear power technologies by 2050. The vast majority of additional nuclear power over the next 30 years will take place in China. In the *Drawdown (PDS2)* and *Optimum Scenarios (PDS3),* the market share reaches 8.6 percent despite having the same adoption (higher TAM) and 0 percent due to the scenario key assumption of 100% RES by 2050, respectively. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percent. Figure 3.1 depicts the long-term pathway trajectories for the different scenarios of nuclear energy.

Table 3.1 World Adoption of the Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| **Plausible** | **Drawdown** | **Optimum** |
| Nuclear Power | *Electricity Generation (TWh)* | 689 | 6,093 | 6,093 | 0 |
| *(% market)* | 3.06% | 13.4% | 8.6% | 0% |

Figure 3.1 World Annual Adoption 2015-2060

## Climate Impacts

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

The *Plausible Scenario* results in the avoidance of 3.25 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. *Drawdown scenario* has the same impact as the *Plausible scenario.* *Optimum Scenario* projects a declining trend of nuclear power use with negative impacts on greenhouse gas emissions reductions over 2020-2050 of -55.4 gigatons of carbon dioxide-equivalent, but with several other important environmental, economic and social benefits. 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*** | 0.15 | 3.25 | 0.15 |
| ***Drawdown*** | 0.15 | 3.25 | 0.15 |
| ***Optimum*** | -0.45 | -55.42 | -0.45 |

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined). After integration, the impact on emission reduction for this solution is 2.9 gigatons of carbon dioxide-equivalent in the *Plausible and 3.2 in the Drawdown* scenario. Since one of the key assumptions of *Optimum* scenario is no nuclear by 2050 the adoption of nuclear presents a negative impact on GHG emissions reduction compared to a REF scenario. 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** | 0.27 | 0.008 |
| **Drawdown** | 0.27 | 0.008 |
| **Optimum** | -4.61 | -0.21 |

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

## Financial Impacts

The results of the *Plausible* Scenario show that the net cost compared to the *Reference* Scenario would be US$192 billion from 2020-50, with slightly over US$158 billion in net operating savings over the same period. PDS1 adoption increasing electricity generated from nuclear power from 2,700 to 6,093 TWh by 2050 would require an estimated US$4,2 trillion in cumulative first costs.

PDS2 results show US$192 billions of marginal first costs and over US$159 billions of net operating cost savings. Due to the reduction to zero by 2050 of electricity generated by nuclear, the marginal first costs are US$3,683 with negative net operating savings of US$2.7 trillion. 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** | 4,197 | 192 | 159 | -49 |
| **Drawdown** | 4,197 | 192 | 159 | -49 |
| **Optimum** | 219 | -3,683 | -2,732 | 428 |  | 159 | -49 |

Figure 3.3 World Operating Cost Reduction (2015-2060)

# Discussion

The results of the nuclear energy solution indicate that nuclear power can form an important part of a low-carbon economy, leading to significant reductions in greenhouse gas emissions with net savings. The emphasis of this study is on climate and financial impacts of NPPs and does not provide a total cost-benefit analysis of every advantage and disadvantage of nuclear power based on fission.

## Limitations

The scope of work for Drawdown nuclear energy solution portrayed in this report and solution model is limited to the commercially deployed NPP units as of 2014. Other promising nuclear power designs, from small modular reactors to high temperature gas cooled reactors, were not discussed. Further development of this solution could add advanced designs as they become commercially available.

Two of the most common reactors are Pressurized Water Reactors and Boiling Water Reactors, both of which are light water reactors that use ordinary water to cool and heat the nuclear fuel. The focus of the literature review has been mostly on PWRs as the dominant type of current, and predicted future, fleet of NPPs. Further development of this study may include nuances between PWRs and BWRs.

## Benchmarks

Table 4.1 depicts a benchmark of Project Drawdown results for 2050 on the three developed scenarios to other nine publicly available scenarios from for example Greenpeace (2015), IEA ETP (2017), IEEJ 2019 (2018) and Ram *et al* (2019). (Table 4.1).

Table 4.1 Benchmarks

|  |  |  |
| --- | --- | --- |
| **Source and Scenario** | **Electricity Generation in 2050 (TWh)** | **Market Share in 2050 (%)** |
| **Project Drawdown – Plausible Scenario (PDS1)** | **6,093** | **12.2%** |
| **Project Drawdown – Drawdown Scenario (PDS2)** | **6,093** | **8.6%** |
| **Project Drawdown – Optimum Scenario (PDS3)** | **0** | **0%** |
| Greenpeace Energy [R]evolution (2015) – Reference Scenario | 4,054 | 8.1% |
| Greenpeace Energy [R]evolution (2015) – Energy Revolution Scenario | 0 | 0% |
| Greenpeace Energy [R]evolution (2015) – Advanced Energy Revolution Scenario | 0 | 0% |
| IEA Energy Technologies Perspectives (2017) – Reference Technology Scenario | 4,951 | 16.0% |
| IEA Energy Technologies Perspectives (2017) – 2DS | 6,932 | 16.3% |
| IEA Energy Technologies Perspectives (2017) – B2DS | 7,069 | 16.0% |
| IEEJ Outlook 2019 (2018) – Reference Scenario | 3,496 | 7.5% |
| IEEJ Outlook 2019 (2018) – Advanced Technologies Scenario | 5,685 | 13% |
| Ram *et al*. (2019) | 194 | 0.3% |

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# Glossary

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

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

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

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

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

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

**Discount Rate**- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis 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.

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

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

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

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

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

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

1. Current adoption is defined as the amount of functional demand supplied by the solution in 2018. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated [↑](#footnote-ref-1)
2. 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-2)