TECHNICAL ASSESSMENT FOR HIGH-EFFICIENCY HEAT PUMPS

SECTOR: BUILDINGS

AGENCY LEVEL: BUILDING OWNERS

KEYWORDS: BUILDING EFFICIENCY, BUILDING SYSTEMS, HEATING AND COOLING, GROUND SOURCE HEATING, AIR SOURCE HEATING

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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

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ACRONYMS AND SYMBOLS USED

- AHRI – Air-conditioning, Heating and Refrigeration Institute
- ASHP – Air-Source Heat Pump
- B2DS – Beyond 2-degree C Scenario (IEA ETP 2017)
- COP – Coefficient Of Performance (Wh/Wh) (for space heating)
- DOE – US Department of Energy
- EER – Energy Efficiency Ratio
- EHPA – European Heat Pump Association
- EIA – Energy Information Agency (US DOE)
- GHG – Greenhouse Gas
- GSHP – Ground-Source Heat Pump
- GWP – Global Warming Potential
- HEHP – High-Efficiency Heat Pump
- HSPF – Heating Seasonal Performance Factor (BTU/Wh) [US metric]
- HVAC – Heating, Ventilating And Air Conditioning
- IEA – International Energy Agency
- IEA ETP – International Energy Agency - Energy Technology Perspectives Report
- IPCC – Intergovernmental Panel on Climate Change
- kW - Kilowatt
- kWh – Kilowatt Hour
- MEPS – Minimum Energy Performance Standards
- NPV – Net Present Value
- PDS – Project Drawdown Scenario
- REF – Reference Scenario (Project Drawdown)
- RTS – Reference Technology Scenario (IEA ETP 2017)
- SCOP – Seasonal Coefficient Of Performance (Wh/Wh) (for space heating)
- SEER – Seasonal Energy Efficiency Ratio (Wh/Wh) (for space cooling) [BTU/Wh in the US]
- TAM – Total Available Market
- TW/ TWh – Terawatt/ Terawatt Hour
- 2DS – 2 Degrees C Scenario (IEA ETP 2017)
- Wh – Watt-hour
- WSHP – Water-Source Heat Pump

EXECUTIVE SUMMARY

This analysis indicates that high-efficiency heat pumps (HEHPs), if widely adopted, could provide 40% of building space heating delivered energy by 2050. The result, detailed in the Drawdown Scenario, would be a reduction of 9.4 Gt of 2020-2050 CO_2 emissions compared with the Reference Scenario. This would reduce atmospheric GHG concentration by 0.77 PPM CO_2-equivalent in 2050. Lifetime operating cost savings would total $2.49T from 2020 to 2050, with a lifetime cash flow savings NPV of $0.58T. Applying HEHPs to building space cooling could deliver similar scale benefits.

High-efficiency heat pumps – those with seasonal coefficient of performance (SCOP) of 3.5 or greater – are commercially available today. And heat pumps installed in 2050 are expected to have average SCOP of 3.9. Yet, in 2014 heat pumps provided only about 3% of space heating delivered energy worldwide.

Some of the key barriers and challenges to future adoption of HEHPs for space heating include:

- Competition against low-cost CO_2-emitting fossil fuels.
- Relatively high HEHP first cost compared with other space heating equipment.
- Reduced efficiency and capacity in very cold weather.
- Increased electricity demand and altered seasonal and diurnal peak loads for many utilities.
- Increased potential for refrigerant leakage contributions to GHG emissions (though the world is moving to low-GWP refrigerants, leakage could be a major concern with such a vast scale up).

Key success factors, proven in the past, and needed to accelerate future HEHP global adoption include:

- Integrated government policies incorporating a clear vision of energy consumption / GHG emissions objectives and increasingly high minimum performance and standards (MEPS).
- Financial incentives for preferred HEHP system installations to help buyers consider not only first cost, but future operating cost (50% to 80+% of lifecycle HEHP cost).
- Accurate, informative labeling supported by relevant performance metrics.
- Avoidance of "stranded asset" investments, for example, in no-longer-needed gas transmission / distribution networks.
- Continued HEHP industry collaboration with other industries, academia, and government.
- Ongoing heat pump technological improvement and cost reduction, especially:
    - Expanded employment of efficiency improvements that already exist in many commercial high-efficiency units.
    - Improved efficiency and capacity at very low outdoor temperatures.

1 LITERATURE REVIEW

Globally, the buildings sector is one of the largest end-use sectors, accounting for 30% of global final energy usage. Including building construction increases this to 36%. These two together account for 39% of energy-related CO_2 emissions (UN Environment & IEA, 2017). Thus, the global building sector needs innovative technologies and approaches to reduce energy consumption while ensuring building operations are not affected. Breaking down the building sector by energy end-use gives us an idea of where the potentials lie. Space heating consumed 32% of final building energy in 2014. The other top uses are cooking energy (22%), water heating (19%), appliances and equipment (16%), and lighting (6%) (IEA, 2017). Clearly there are many opportunities across the building sector for energy efficiency. Space and water heating energy is affected by windows walls and heat source; cooking energy is affected by source and cooking technology; appliance energy by appliance efficiency and use; and lighting is affected by light technology and use.

1.1 THE STATE OF HIGH-EFFICIENCY HEAT PUMPS FOR SPACE HEATING AND COOLING

"High-Efficiency Heat Pumps" (HEHP) for building space heating and cooling can have major impact in reducing greenhouse gas (GHG) emissions worldwide. In 2014, the global buildings sector consumed 123 exajoules (EJ) of energy. Of this, space heating consumed over 39 EJ and space cooling 6 EJ of final energy consumption (IEA, Energy Technology Perspectives, 2017). So, by reducing building space heating and cooling energy consumption, high-efficiency heat pumps can significantly reduce global energy use and GHG emissions.

High-efficiency heat pumps can have widespread and cost-effective application. HEHPs can be installed in new construction and usually can be retrofitted into existing buildings, especially air-source units. As a high-efficiency space conditioning solution, operating cost savings can far outweigh added first cost. The result can be high financial return, in addition to energy savings and GHG reduction.

1.1.1 What is a heat pump and how does it work?

A "heat pump" is a device that uses electrical energy to *transfer* heat from one location to another. While heat naturally flows from a high-temperature source to a low temperature sink, a heat pump uses electrical energy to provide the work required by the second law of thermodynamics to transfer heat (thermal energy) from a low-temperature source to a high-temperature sink. Thus, a heat pump can extract thermal energy from cold outdoor air in winter to heat a building, or in summer provide space cooling by rejecting heat from a building to the hot ambient.

It is this thermodynamic wrinkle of *transferring* heat from an available reservoir – and not creating it – that enables heat pumps to operate at efficiencies above 100%. By contrast, conventional furnaces and boilers *create* heat by combusting fossil fuels, most commonly natural gas or fuel oil, thus converting the chemical energy of the fuel into thermal energy, with CO_2 as a byproduct. Furnaces and boilers typically operate at conversion efficiencies of 70% to 80%; high-efficiency units can reach 90% to 95% efficiency (IEA, Energy Technology Perspectives, 2017, p.129). But the first law of thermodynamics limits the theoretical primary energy conversion efficiency of any such combustion-based heating appliance to 100%. No combustion-based heating appliance can exceed this limit.

In this report "heat pump" embraces the full range of space heating and cooling applications, heat pump types, sizes, and heat sources / sinks:

- Space heating, space cooling or both
- Residential room air conditioners and heat pumps
- Residential central units, both split and packaged designs
- Commercial split and packaged heat pumps and air conditioners
- Commercial air- and water-cooled chillers
- All size ranges from less than 1 kW up to 10,000+ kW giant commercial chillers
- Air-source, ground-source, and water-source heat pumps

The Electric Vapor Compression Heat Pump

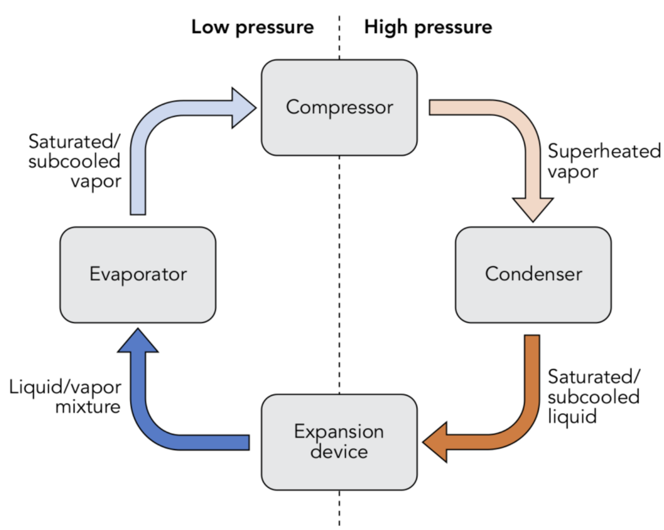

Figure 1.1. Heat pump vapor compression cycle

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Though many refrigeration cycles have been developed, e.g., thermoelectric, absorption, etc., virtually all commercial heat pumps for building space heating or cooling operate via electrically powered "vapor compression" and expansion of a working fluid (refrigerant). Figure 1.1 illustrates the operating cycle of a vapor compression heat pump and its four main components: evaporator, condenser, compressor, and expansion valve.

Evaporator: The evaporator is a low-temperature heat exchanger. The refrigerant enters the evaporator as a low temperature liquid and absorbs heat from the heat source (indoor conditioned space for cooling applications or outdoor non-conditioned space for heating) and is evaporated into a low-density, low-temperature gas before entering the compressor.

Compressor: The electrically driven compressor provides the work that compresses the low-temperature refrigerant gas from the evaporator, raising its pressure and temperature.

Condenser: The now hot, high pressure refrigerant gas rejects heat to the condenser heat sink (indoor conditioned space for heating and outdoor non-conditioned space for cooling) before entering the expansion valve as a high-temperature liquid.

Expansion valve: The expansion valve is a "throttling device" that rapidly reduces the temperature and pressure of the hot liquid refrigerant, resulting in a low-temperature, low-pressure liquid/vapor mixture.

Reversing valve (not shown): All heating-only or cooling-only heat pumps contain these four components. Dual mode heat pumps that provide both heating and cooling, in addition contain a valve to reverse the refrigerant flow, thus switching the refrigeration cycle from heating mode to cooling operation.

By this four-step cycle of evaporation, compression, condensation, and expansion of the refrigerant, a heat pump extracts heat from a low temperature source and transfers it to a high temperature sink. The value of this approach is that, although some external electrical energy is required, the amount of heat energy transferred from the heat source to the heat sink can be several times the amount of work required to power the compressor.

Heat Pump Varieties

Commercially available heat pumps use three main ambient heat sources/sinks for space heating and cooling:

- *Air-source heat pumps (ASHP),* the most common version, absorb heat from outdoor air to heat the indoors in winter. In summer, the same heat pump can be run in the reverse mode to absorb heat from indoors and reject it to the outdoor air. In residential applications, in the USA where gas-fired furnaces and air conditioning (and associated ductwork) are widespread, air-air heat pumps are most popular. In Europe, where residential space cooling is less common and hydronic heating systems are the norm, air-water heat pumps[1] are more popular.

- *Ground-source heat pumps (GSHP*) exchange heat with the ground using serpentine buried pipes or sealed wells. In winter, a GSHP absorbs heat from the ground and uses it to heat the indoor space. During summer months, this process is reversed (see Metz, 1984). Because the ground temperature is usually more moderate than ambient air temperature – warmer in winter and cooler in summer – GSHPs operate at higher efficiency than ASHPs, especially in climates with extreme ambient temperatures. Access to the ground, and the additional first cost of the ground-source piping, limits the applicability of GSHP systems.

- *Water-source heat pumps (WSHP)* extract energy from ground water or rivers and streams. Analogous to GSHPs, WSHPs can operate more efficiently than ASHPs in many locations. Likewise, too, access to a suitable water source and a place to reject the water limits applicability.

Air-source heat pumps are the prime focus of this report: Because of the ubiquity of the air heat source / sink, and lower installation cost, ASHPs are by far the most common variety of heat pump and air conditioner. And it is worth noting that there is great opportunity for future improvement of ASHP performance, reliability and cost (see below), with much ongoing research. For example, research continues to address a major limitation of ASHPs in cold climates – reduced efficiency and low heating capacity at very low outdoor air temperatures, just when heat is most needed (IEA, HPT TCP Annex 41 Final report Cold Climate Heat Pumps, 2017).

Research also continues on "next-generation heat pumps" including advanced vapor compression cycles, non-vapor-compression cycles (e.g., solid state or electro-chemical), integration with other building systems (such as air conditioners that share waste heat with other building systems), gas engine heat pumps, and multi-function devices (e.g., heating, cooling and hot water) (Goetzler, 2016). But these are not significant commercial products today and are not further addressed in this report.

Measuring Heat Pump Performance

Clear, reliable performance metrics are critical for a heat pump buyer to make an informed purchase decision that balance first cost investment against future energy use and operating cost. In this way, accurate performance metrics enable customers worldwide to save money, while reducing purchased energy and corresponding GHG emissions.

[1] This is an air-source heat pump that passes heat to the hydronic (water) piping in the building.

It would be ideal to have a single measure of heat pump seasonal performance. Such a metric would at minimum provide a simple, accurate way to estimate heat pump purchased electricity, energy delivery, and GHG emissions in actual use; and also serve as the basis for comparing alternative space conditioning options. The reality is a web of not-quite-comparable metrics:

"Single-point performance metrics" have been used for years but, since they reflect performance at only one set of operating conditions, they have limited value for calculating seasonal performance and operating cost. Key single-point metrics include:

- **Coefficient of Performance (COP)** describes the efficiency of a heat pump. COP is a dimensionless ratio (Wh/Wh) of the heating (or cooling) energy the heat pump delivers to the electrical energy consumed by the heat pump. COP normally refers to *instantaneous performance* at a single set of specified operating conditions, so it is not adequate for estimating seasonal performance (IEA HPT, Efficiency and Heat Pumps website).

- **Energy Efficiency Ratio (EER)** is a US variant of COP for space cooling. EER is steady-state efficiency at 95F (35C) outdoor temperature and 80F (27C) indoor temperature in units of BTU/Wh (so EER rating is 3.412 times the COP rating at the same conditions). Though widely used in the past, EER is not a good indicator of seasonal performance; as a single-point metric, EER ratings do not correlate well with experimentally measured seasonal efficiency which depends on part-load operation, especially in temperate climates (Fairey, 2004). Europe has used a dimensionless (Wh/Wh) version of EER in the past; this "EU EER" equals COP for the stated operating conditions (Lacourt, 2018).

Seasonal performance metrics, which more accurately reflect real-world heat pump performance, are supplanting single-point metrics in heat pump rating:

- **Seasonal Energy Efficiency Ratio (SEER)** is the metric for seasonal cooling performance: the total heat removed from the conditioned space during the annual cooling season divided by the total electrical energy consumed by the air conditioner or heat pump (including all pumps, fans, controls, etc.). SEER comes closer to estimating actual seasonal performance by weighting performance across multiple outdoor temperature bins and incorporating part-load effects and other factors (AHRI, 2008). In the US, SEER is expressed in BTU/Wh, codified into law (10 Code of Federal Regulations (CFR) § 430.B, App. M, 2018), and used as the basis for ENERGY STAR space cooling equipment rating. Though US SEER ratings in principle can be calculated for any location, US published ratings usually reflect only US Climate Region IV performance. Region IV, which includes New York City and Seattle, is representative of temperate locations, but doesn't accurately portray heat pump performance in very cold or hot humid locations (Fairey, 2004). Europe has a similar SEER system (here labeled "EU SEER" to distinguish from US SEER ratings) with two main differences: EU SEER ratings are dimensionless (Wh/Wh); additionally, EU SEER uses different temperature bins and calculation procedures (EN 14825), so that EU SEER ratings are not exactly convertible to US SEER ratings simply by dividing by 3.412. The European Union classifies air conditioners and heat pumps based on EU SEER; it is gradually imposing minimum energy efficiency standards based on EU SEER ratings (Lacourt, 2014; Lacourt, 2018). Overall, with caveats recognized, SEER provides a reasonably accurate estimate for heat pump seasonal cooling performance.

- **Heating Seasonal Performance Factor (HSPF)**, analogous to SEER, is the US metric for seasonal heating performance and is the total space heating provided in Region IV during the space heating season, expressed in BTU, divided by the total electrical energy consumed by the heat pump system during the same season, expressed in Wh. Like SEER, HSPF has been codified into law (10 Code of Federal Regulations (CFR) § 430.B, App. M, 2018), and used as the basis for ENERGY STAR space heating equipment rating. Europe uses a similar metric, **Seasonal Coefficient of Performance (SCOP)**, expressed in Wh/Wh, to measure heating seasonal performance. Like EU SEER, SCOP calculations are based on EN 14825. And like SEER, HSPF and SCOP provide a reasonably accurate estimate for heat pump seasonal heating performance.

This report adopts the following dimensionless ratios to characterize heat pump seasonal performance, essentially adopting European practice (noting other metrics when needed):

- **Heating seasonal performance measure: SCOP (Wh/Wh)**
- **Cooling seasonal performance measure: SEER (Wh/Wh)**

1.1.2 What is a high-efficiency heat pump and how can it reduce GHG emissions?

This report characterizes heat pumps as "high efficiency" when:

- Efficiency is sufficiently superior to "market average" heat pumps to yield substantial energy savings and corresponding GHG emissions reductions over market average units.
- Existing market presence is sufficient to ensure that large-scale implementation is technically feasible and economically practical.

Space Heating HEHP SCOP

Based on these criteria for space heating, a high-efficiency heat pump is defined as having seasonal coefficient of performance SCOP of 3.5 Wh/Wh or greater: on a seasonal average basis it delivers 3.5 Wh of heat for every 1 Wh of electricity consumed. This equates to US HSPF of approximately 12 BTU/Wh.

Table 1.1 provides heating seasonal SCOP data for a wide range of heat pump types and sizes worldwide. As the table illustrates, "average" heat pump SCOPs range from about 2 to 3. Minimum efficiency requirements for new heat pumps, and for heat pumps to receive renewable energy incentives, range from 3.0 to 3.5. The "most efficient" air-source heat pumps achieve SCOP ratings of 4.0. Ground source heat pumps, both closed and open loop, both water-air and water-water, have SCOP ratings of 3.6 to 4.1, and so qualify as "high-efficiency".

So, a HEHP SCOP rating assignment of 3.5 is substantially higher than "average" heat pumps achieve. It fits within the range of minimum efficiency requirements for new heat pumps, though below the "most efficient" air-source heat pumps commercially available today.

Table 1.1 Heating Seasonal Coefficient of Performance (HCOP) for Selected Heat Pumps Worldwide

SCOP* [Wh/Wh]	Region	Description
4.0	USA	Most efficient air source heat pumps (ENERGY STAR, 2018).
2.8	USA	Air-source heat pump split systems; minimum to be recognized as "most efficient" (ENERGY STAR, n.d a-f).
2.5	USA	Air-source heat pump split systems; minimum to be rated (ENERGY STAR, n.d a-f).
3.6	USA	Closed loop ground-source heat pump split systems; minimum to be recognized as "most efficient" (ENERGY STAR, n.d a-f).
4.1	USA	Open loop ground-source heat pump split systems; minimum to be recognized as "most efficient" (ENERGY STAR, n.d a-f).
3.5	Europe	Minimum efficiency for air-source units to receive incentives under the German MAP program (EHPA, 2014).
3.3	Europe (Germany)	Minimum efficiency for air-source units in new construction (up to 4.0 depending on application) (EHPA, 2014).
3.2	Europe	Rooftop air-air heat pump minimum efficiency requirement 2021 (Lacourt, 2018).
3.1	Europe (Germany)	Air-water "average value" experimental monitoring 2012-13 (Miara, 2014).
3.0	Europe	Rooftop air-air heat pump minimum efficiency requirement 2018 (Lacourt, 2018).
2.6	Europe	Commercial products air-water "average value" (EPHA, 2014).

SCOP* [Wh/Wh]	Region	Description
4.0	Europe	Ground-source water-water "average value" experimental monitoring 2012-13 (Miara, 2014).
3.4	China	Air-source heat pump water heater minimum requirement (EHPA, 2014).

*SCOP reflects seasonal operating efficiency in each country; ratings are not strictly comparable as test conditions differ across countries.

Space Cooling HEHP SEER

In a similar way, for space cooling, a high-efficiency heat pump is defined as having seasonal energy efficiency ratio SEER of 5.9 Wh/Wh or greater. This corresponds with a SEER of about 20 BTU/Wh in US units. For every 1 kWh of electricity consumed, a HEHP delivers 5.9 kWh of space cooling effect.

Table 1.2 provides cooling season SEER data for a wide range of heat pump / air conditioner types and sizes worldwide. As the table illustrates, "average" heat pump SEERs range from 3.9 to 5.3 for units across a wide range of sizes from small ACs to large packaged AC units. "Typical available high efficiency" units have SEERs ranging from 5.6 to 9.0. "Best available" units have efficiencies from 6.9 to 12.3 SEER. Chillers represent a special category suited only for very large buildings; chiller SEERs range from 6.2 to 11.7. So, a HEHP SEER rating of 5.9 is within the range of "typical available high efficiency" units, substantially above "average" heat pump SEERs, but well below "best available" commercial heat pump / air conditioner efficiencies.

Table 1.2. Cooling Seasonal Energy Efficiency Ratio (SEER) for Selected Heat Pumps and Air Conditioners

SEER* [Wh/Wh]	Region	Description
7.9	USA	Most Efficient Central Air Conditioners & Air Source Heat Pumps (ENERGY STAR, n.d a-f).
4.4	USA	The minimum to be rated (ENERGY STAR, n.d a-f).
12.3	USA	Small AC best available (IEA, 2018).
7.6	USA	Small AC typical available high (IEA, 2018).
4.2	USA	Small AC market average (IEA, 2018).
11.0	Europe	Small AC best available (IEA, 2018).
9.0	Europe	Small AC typical available high (IEA, 2018).
5.3	Europe	Small AC market average (IEA, 2018).
7.5	China	Small AC best available (IEA, 2018).
6.8	China	Small AC typical available high (IEA, 2018).
4.4	China	Small AC market average (IEA, 2018).
11.7	Global	Chillers best available (IEA, 2018).

SEER* [Wh/Wh]	Region	Description
11.2	Global	Chillers typical available high (IEA, 2018).
6.2	Global	Chillers market average (IEA, 2018).
6.9	Global	Large packaged AC best available (IEA, 2018).
5.6	Global	Large packaged AC typical available high (IEA, 2018).
3.9	Global	Large packaged AC market average (IEA, 2018).

*SEER reflects seasonal operating efficiency in each country; ratings are not strictly comparable as test conditions differ across countries

How can HEHPs reduce GHG emissions?

High-efficiency heat pumps can reduce GHG emissions by replacing "conventional" HVAC equipment (fossil-fueled furnaces or boilers, electric resistance heating, or low-efficiency heat pumps or air conditioners) in almost any size or type of building where electricity is available, in any country or climate zone in the world, by:

1. **Reducing fossil fuel consumption.** As an electrically-driven space heating solution, HEHPs can substitute renewably-generated electricity, where available, for fossil fuel combustion furnaces and boilers – thus eliminating this source of CO_2 emissions. Hence, renewable electricity generation is important for HEHPs to reduce GHG emissions. And conversely, HEHPs represent a critical enabler for renewable energy to replace fossil energy in building space heating.
2. **Increasing space heating energy efficiency.** For every kWh of electricity consumed, a HEHP delivers 3.5 kWh of space heating energy. Fossil furnaces and boilers, by contrast, typically operate at 70% to 80% primary energy conversion efficiency. Electric resistance heating, too, is limited to 100% electrical-to-thermal energy conversion efficiency.
3. **Increasing space cooling energy efficiency.** HEHPs reduce GHG emissions in space cooling applications by replacing less efficient heat pumps and air conditioners, which often operate with seasonal cooling efficiencies of only 250% to 300% even though units with efficiencies exceeding 600% are commercially available (IEA, Energy Technology Perspectives, 2017, p. 123).

1.2 ADOPTION PATH FOR HIGH-EFFICIENCY HEAT PUMPS

1.2.1 Current Adoption of High-Efficiency Heat pumps

Current Adoption of HEHPs for Space Heating

While global adoption of space-heating heat pumps is substantial and growing, adoption of high-efficiency heat pumps is very low. The IEA estimates that heat pumps provide about 3% of building space heating and water heating worldwide, with installed base SCOPs averaging only 2.0-2.5 (IEA ETP, 2017, p. 145). So, heat pumps are far outnumbered by fossil fuel combustion-based heating gear. And, given the low average efficiency of installed heat pumps, clearly HEHPs with SCOP of 3.5 or more represent only a small fraction of heat pumps currently installed – and thus a tiny fraction of installed space heating equipment.

The two markets with the largest space-heating heat pump adoption, the US and EU, illustrate the situation: In the US, where air-to-air heat pumps predominate, about 14% of commercial building space and 10% of residences use an electric heat pump for heating (EIA, US DOE, 2016, 2017). But, based on industry data from the Air-conditioning, Heating and Refrigeration Institute (AHRI), the US DOE estimated that high-efficiency heat pumps with SCOP above 3.5 (HSPF above 12 BTU/Wh) comprised less than 1% of installed heat pumps in 2015 (US DOE, 2015, p. 3-20).

In Europe, over 50% of heat pumps sold in 2013 use air distribution, driven by sales in warmer countries, including France, Italy, and Spain; about 40% use hydronic distribution, driven by Denmark and Sweden (EHPA, 2014, p. 41). Overall European heat pump market penetration is similar to the US – about 3% to 5% – but a few countries, notably Sweden, Norway and Finland, have far higher penetration rates between 20% and 40% (see below) (EHPA, 2014, p. 45). Ground-source heat pumps, which comprise about 13% of EU sales, qualify as "high-efficiency" with an average efficiency of 3.5 SCOP, but air-source units achieve average efficiencies of only 2.6 SCOP (EHPA, 2014, p. 53). So, as in the US, penetration of high-efficiency air-source heat pumps is small.

In China, air-to-air heat pumps in the form of reversible room air conditioners (RAC) – which are used primarily for cooling and provide limited heating – are common with annual sales over 40 million units (Zhou, 2017, p. 1). Variable refrigerant flow (VRF) air-to-air heat pumps and air-source heat pump water heaters (AHPWH) represent hot categories, selling over 1 million units each annually (Ibid). Sales of air-source heat pumps for hydronic space heating focus mostly on commercial buildings; residential sales are very small (Ibid). Efficiency standards and labeling are inconsistent to date, so estimating installed efficiency is difficult.

Current Adoption of Space Cooling HEHPs

For space cooling, the situation is similar with two "twists": First, almost all building space cooling is already provided by vapor-compression air conditioners or heat pumps – albeit at average SEER for new units of about 4.2 (US SEER of about 14) in 2016 for new units (IEA, Future of Cooling, 2018, p. 42). So, analogous to space heating, penetration of HEHPs with SEER of 5.9 or greater is low and there is great potential for GHG reduction simply by increasing the penetration of existing HEHP technology. In the US, for example, HEHPs with SEER above 5.9 (US SEER above 20 BTU/Wh) represented less than 1% of air conditioners or heat pumps models installed in 2015 (US DOE, 2015, p. 3-16).

The other twist is growth: While space heating demand has risen marginally, demand for space cooling has risen dramatically, especially in developing countries: Between 1990 and 2016 world final energy consumption for space cooling in buildings (the energy *consumed* at the building, almost all electricity, in order to deliver space cooling) rose from 608 TWh to 2021 TWh. While US energy consumption rose from 339 TWh to 616 TWh, about 81%, Chinese space cooling energy consumption rose from 7 TWh to 450 TWh – over 6300% –making China the number two consumer of energy for space cooling, behind only the United States. The European Union and Japan follow at far lower levels with 152 TWh and 107 TWh respectively in 2016 (IEA, The Future of Cooling, 2018, p. 24).

The level of cooling adoption varies greatly by country (IEA, The Future of Cooling, 2018, p.19): The US has the greatest installed cooling stock, with over 4700 GW output capacity. China ranks number two in installed stock, with over 2800 GW output capacity. The EU and Japan are the next largest. In terms of 2016 annual sales, the US leads with 443 GW (9% of installed base), almost tied with China at 386 GW (13% of installed base); sales in all other regions are far lower. However, in addition to China, several developing countries have high sales / installed base ratios: India, 17%; Indonesia, 15%. So, space cooling is growing rapidly in hot developing countries.

The nature of cooling equipment adoption also varies greatly by country, climate, and culture. In the US, space cooling is ubiquitous, with virtually all commercial buildings and almost 90% of residential buildings reporting some form of electrically driven space cooling. The majority, in both markets, report central AC or heat pump systems, with the remainder employing individual ACs or heat pumps (EIA, US DOE, 2016, 2017). By contrast, in Europe, also with a high level of affluence, the space cooling market is mostly commercial with less than 10% of households owning ACs (partly as a result of a cooler climate). China had the highest level of residential AC sales, about 40 million units, and one of the highest per capita sales ratios – 30 units per 1000 people - in 2016 (IEA, The Future of Cooling, p. 21) .

1.2.2 Trends to Accelerate Adoption of High-Efficiency Heat Pumps

To shed light on the trends to accelerate adoption of HEHPs, it is valuable to examine the adoption of heat pumps to date, especially high-efficiency units. What are the key drivers that have propelled the market in the direction it has taken? What issues have influenced adoption? What are the "key success factors" that have made HEHPs grow? What are the barriers that have impeded progress? And how might these factors change in the future?

Drivers and Issues Affecting HEHP Adoption

Main drivers and issues influencing the nature and speed of high-efficiency heat pump adoption include:

- **Comfort and affluence:** The main force driving heat pump growth, from the early days when practical commercial and residential space heating and cooling first emerged until the present, has been the combination of the desire for comfort – especially for cooling – coupled with the affluence to afford it. When space cooling became practical for almost all buildings decades ago, with development of factory-manufactured units and safe refrigerants, this combination was a major factor in economic development in the US South; and it has been a driver of air conditioning growth in China over the past 20 years; it continues to drive air conditioning penetration in India and other hot developing countries.
- **Development of reversible heat pumps:** Establishment of space cooling, for which vapor compression has been the only practical solution in most locations, "opened the door" for reversible heat pump *space heating*. In regions with hot summers and mild winters, such as the US South and much of China, reversible heat pumps have provided a low-added-cost space heating solution. The space cooling infrastructure has also expedited heat pump space heating adoption by providing the technological foundation, manufacturing base, and skilled technician pool needed for space heating.
- **Ease of installation:** Air-source heat pump installation, on average, is similar in complexity and disruption to installing a fossil furnace or boiler. For heating-only retrofits, an existing hydronic or air distribution system usually can be used. Sometimes the existing distribution system may need to be augmented with additional heat exchange capacity, especially if it is an older system designed for steam or very hot water, because the heat pump may provide lower-temperature heat. (This may represent a good opportunity to update the building envelope instead.) Outdoor air access is needed, but this is not significantly different for fossil-based heating systems which require outdoor access for combustion air intake and exhaust. In some respects, ASHP installation is simpler, not requiring fuel piping, and providing both heating and cooling in a single system. Space cooling usually requires an air distribution system (as opposed to hydronic) in order to address dehumidification

(possibly excepting “chilled beam” systems, which are not common; see for example Murphy, 2011). This may add cost and complexity in locations where hydronic distribution is prevalent.

- **Cost:** First cost and operating cost are very location-dependent and building-specific. This report addresses cost below under “Barriers” in Section 1.2.3.
- **Location:** Historically, reduced efficiency and low heating capacity at very low outdoor air temperatures, have limited the viability of ASHPs in very cold climates. This report addresses location below under “Barriers” in Section 1.2.3.
- **Installation skills and equipment availability:** With the widespread implementation of vapor compression space cooling in the US, Europe, China and other markets, skilled ASHP installers (and engineers to operate large commercial buildings) are widely available throughout these regions. Availability of skilled people and equipment can be a problem in developing countries where space cooling is less prevalent, and the equipment / parts supply chain is weak.
- **Large building implementation:** Large commercial buildings space conditioning needs are quite different from those of residential structures or small commercial buildings. It is common for a large building – due to its high volume to surface area ratio – to require space heating and space cooling in different parts of the structure at the same time. This is especially true in temperate climates during cooler times of year when perimeter heating and central core cooling are needed simultaneously. Likewise, large buildings require active measures to provide fresh air ventilation and to remove CO_2 from densely-occupied spaces – functions provided in small buildings by envelope leakage. And many large commercial buildings have special space conditioning needs: Hospitals, for example, require very high ventilation rates and special temperature / humidity conditions in operating rooms and other specialized spaces. And increasingly, commercial buildings contain computer data centers with intense cooling requirements. As a result, the space conditioning systems employed in large commercial buildings are quite different from those in small buildings. Large buildings often employ large chillers for space cooling, and typically use variable air volume (VAV) terminal-based heating and cooling distribution systems. With thousands of sensors and actuators to control, a building automation system (BAS) is mandatory. Large commercial buildings offer unique energy-saving challenges and opportunities not seen in smaller buildings: As an example, to meet comfort and ventilation requirements, VAVs often wastefully “reheat” previously cooled air using fossil-heated water or electric resistance coils. On the opportunity side, the need for simultaneous heating and cooling makes it possible to use space cooling reject heat to provide space heating or domestic hot water. And large chillers can use

"economizer cycles" when the outdoor temperature is low to provide "free" space cooling. In temperate climates, this can dramatically reduce cooling energy consumption.

Key Success Factors to Accelerate HEHP Adoption

What are the "key success factors" needed to accelerate HEHP adoption?

1. **Integrated government policy including:**

   - **Vision.** Overall energy consumption / GHG emissions objectives and strategic frameworks at international, national, and local levels.
   - **Minimum Energy Performance Standards (MEPS).** Increasingly high MEPS (sometimes articulated as renewable content standards) provide a critical "demand signal" for heat pump manufacturers to invest in the design, manufacture, and sale of high-efficiency heat pumps. MEPS have been a major factor in driving adoption of energy efficient heat pumps worldwide (Goetzler, 2018, p. 51; IEA, Future of Cooling, 2018, p. 67). The US DOE has regularly updated heat pump / AC minimum efficiency standards, which are now regional, (Regulations, 2016; Regulations, 2017), resulting in huge energy savings and hundreds of billions of dollars of reduced operating costs (Goetzler, 2018, p.29). The EU, too, has imposed increasingly strict minimum performance standards. These have evolved from "standard rating condition" single point efficiency metrics, such as EER and COP, to seasonal efficiencies SEER and SCOP that set minimum requirements for the "renewable energy" contribution from heat pumps (Lacourt, 2018). Voluntary standards, such as ENERGY STAR in the US, and various incentive programs in Europe (see e.g., EHPA, 2014) also make an important contribution. A counter example in standard setting is China which, as of 2017, lacked unified energy efficiency standards and labeling, making it difficult for buyers to evaluate products (Zhou, 2017).
   - **Financial incentives for preferred HEHP system installation.** Together with MEPS, financial incentives provide a "carrot and stick" to influence HP buyers to consider, not only first cost, but also future operating cost (which comprises 50% to 80% of total HEHP cost (Goetzler, 2018, p. 42)), energy use, and GHG emissions. And many buyers need loans or other support to purchase new equipment. Incentive programs are diverse, typically involving upfront equipment purchase rebates, financing or tax abatement to reward high-efficiency and "renewable energy" content. This can be defined differently in different regions: For example, both GSHPs and WSHPs are eligible for a geothermal energy tax credit in the USA (ENERGY STAR, Federal Tax Credits: Geothermal Heat Pumps), though technically such systems do not draw on geothermal energy. Many European countries offer heat pump tax credits and other incentives, usually for installing a high-performance unit, and not directed at specific technologies (EHPA, 2014). For example, the German

Marktanreizprogramm (MAP) incentive rewards air-to-water systems with SCOP of 3.5 and ground-source systems with 3.8 SCOP. Sweden, which sets maximum energy demand requirements on all new buildings, pays up to 50% of labor costs for heat pump retrofit installations (EHPA, 2014, p.155). China has provided, at local and national levels, a variety of incentives for different types of HEHPs, especially to reduce coal consumption (Zhao, 2018).

- **Comparative labeling and seasonal performance metrics.** Accurate, informative labeling, supported by relevant performance metrics, represents a simple but powerful tool for equipment specifiers and building owners to evaluate heat pump energy efficiency and lifecycle cost. Labeling, with a foundation of accurate seasonal performance metrics such as SEER and SCOP, has been hugely important for HEHP success. Important labeling programs include the US ENERGY STAR, EU Eurovent (which is being revamped to address seasonal efficiency and renewable energy capture), and Top Runner in Japan (Goetzler, 2018, p. 29-32; Lacourt, 2018). Such programs help customers to identify high-efficiency equipment and to better assess first cost / operating cost tradeoffs. Labeling programs also create visibility and competition, encouraging manufacturers to design high-efficiency products to "make the list".

2. **Heat pump industry collaboration with other industries, academia, and government:** Over the last several decades, the heat pump industry has repeatedly demonstrated its willingness and ability to "step up" to work collaboratively with government and other industries in order to address heat pump challenges. Early challenges included improving heat pump reliability and refrigerant safety (e.g., replacing ammonia and hydrocarbons). Subsequently, under the 1987 Montreal Protocol, the industry redesigned all products in order to implement a completely revamped refrigerant suite, replacing ozone-depleting refrigerants. Today's challenges include increasing energy efficiency in order to reduce heat pump GHG emissions and to cut operating cost, and once again revamping the refrigerant suite, this time to reduce global warming potential (GWP) of the refrigerants themselves. At the end of the day, it is manufacturers who decide to invest – or not – in the design, manufacture, and sale of high-efficiency heat pumps. Thus, industry collaboration has been critical for advancing HEHPs.

3. **Utility energy efficiency programs and incentives:** Utilities also foster purchase of HEHPs via rebates, special "heating rate tariffs", and other incentives to offset the incremental cost of high-performance equipment (Goetzler, 2018, p. 30). In the past, electric utilities promoted all forms of electric heating, including inefficient resistance systems. And low-cost, plentiful electricity has been

an important driver of heat pump growth. But today, utilities, under pressure from government, more typically promote high efficiency.

4. **Ongoing heat pump technological improvement and cost reduction.** No breakthroughs are required to achieve the performance levels defined as "high efficiency": 3.5 SCOP for heating and 5.9 SEER for cooling. Mostly, it is necessary to:
   - Expand penetration of the efficiency improvements already used in many commercial high-efficiency heat pumps (Goetzler, 2018, p. 31, p. 33) (US DOE, Technical Support Document, 2015, Sec. 3.3).
   - Continue the existing cost reduction trajectory (Goetzler, 2018, p. 33, p. 40).

   Heat pump efficiencies have increased more than 50% over the last 25 years; average US residential AC efficiency has increased from about 9.5 BTU/Wh in 1990 to about 15 BTU/Wh today. Equipment costs declined about 15% over the same period, despite the increased efficiency and a major refrigerant transition (Goetzler, 2018, pp. 29, 40). Commercial vapor compression-based heat pumps and air conditioners have always operated far from the theoretical ideal thermodynamic cycle (the Carnot performance frontier). So, these large improvements in heat pump efficiency resulted not from a single technological breakthrough, but from a stream of incremental improvements (Goetzler, 2018, p. 31; US DOE, Technical Support Document, 2015, Sec. 3.3). Going forward, areas for continued innovation include:

   - Variable speed drives and controls to match output to part-load demand, greatly increasing part-load efficiency.
   - Advanced compressors, including improved reciprocating units, small scroll compressors, and multi-compressor large systems.
   - Improved heat exchangers, e.g., microchannel and other small diameter designs.
   - Electronic expansion valves that provide superior modulation for part-load operation.
   - High-efficiency fans with more aerodynamic designs.
   - High-efficiency motors and electronic speed controls.
   - Advanced heat pump controls.
   - Economizers, which enable direct use of cooling energy from cooling towers or outdoor air without compressor operation, especially in temperate climates.
5. **Integrated framework.** It is clear that multiple factors have contributed to HEHP success. But how have those countries that have been most successful at adopting high-efficiency heat pumps done it?

The data shows that an integrated framework, involving government, the private sector, academia, as well as energy purchasers, can have a huge impact. Key ingredients for such a successful framework include: (Nowak, 2017, p. 5; IEA, Future of Cooling, 2018, p. 75)

- Vision of success.
- A strategic plan for delivering the vision.
- A policy suite combining regulation of heat pump MEPS and building envelope standards, HEHP incentives, and product labeling.
- Support for heat pump R&D.
- Industry-government collaboration.
- Investment prioritization: If building fossil fuel use is "out" it is important to avoid investments that could become "stranded assets"; for example. in natural gas transmission / distribution networks that will not be needed (IEA ETP, 2017, p. 140, 146).

Sweden provides a strong example of an integrated framework that has driven HEHP success. Swedish residential heat pump adoption is the highest in Europe, at 40% to 50% (EHPA, 2014, p.45), and renewable energy production, i.e., heat pump efficiency, is second highest (EHPA, 2014, p. 9). Sweden also has the highest adoption of high-efficiency ground-source heat pumps. Sweden achieved all this through a long-term effort that combined industry-driven R&D collaboration on cold-climate heat pumps, especially ground-coupled units, strict building energy consumption standards, heat pump MEPS, as well as financial rebates for heat pump retrofit installations.

1.2.3 Barriers to Adoption of High-Efficiency Heat Pumps

Several key factors have impeded adoption of high-efficiency heat pumps:

- **Low energy prices.** Especially in the US, low energy prices, particularly low-cost natural gas, have been a barrier to space-heating HEHP adoption – even as low electricity prices spurred air conditioning adoption.
- **First cost.** Customers naturally focus on first cost. Accurately balancing operating cost and other benefits is challenging, even for experts, so performance labeling plays a valuable role. Even when the savings calculation can be done accurately, though, first cost can be a barrier for customers who lack the capital to buy an efficient product. In construction, the competitive bidding process can drive subcontractors to propose a lower-first cost option – unless a high-efficiency unit is specified. The inability of some heat pump buyers to "appropriate" (or capture) the benefits of increased heat pump operating efficiency is also a major factor that drives some heat pump purchasers to focus

only on first cost. "Appropriability" is especially a problem in residential or commercial "spec construction" where a developer constructs a building on the "speculation" that he can sell it. Spec construction tends to be intensely driven by first cost because the developer's focus is minimizing their first cost, not future operating cost – which the building owner will face. A similar issue arises in tenant-occupied buildings. Often the tenant is responsible for energy operating costs but lacks the power to alter the HVAC system. The builder and the landlord don't pay operating costs and so may not be concerned about energy efficiency – unless it affects occupancy.

- **Cold weather performance.** ASHPs suffer reduced efficiency and low heating capacity at very low outdoor air temperatures, just when heat is needed most. Historically, this has limited the viability of ASHPs in very cold climates and led to reduced heat pump lifetimes. Performance has improved with the advent of variable speed drives and controls, as well as multi-compressor systems. But improving cold weather performance is still an important active research topic (IEA, HPT TCP Annex 41 Final report Cold Climate Heat Pumps, 2017).
- **Lack of design / installation experience**. Obtaining skilled installers and operating technicians can be a problem in locations with a low installed heat pump base. This is mostly a problem in developing countries today.
- **Access to "ambient heat".** Access to the ground or to a suitable body of water are barriers to high-efficiency GSHP and WSHP systems:

Going forward, HEHPs will need to address several additional new challenges if they are to achieve the ubiquity that has been forecast for them:

- **Availability of renewably-generated electricity**. Electric heat pumps have unique *potential* to reduce GHG emissions, but a 3.5 SCOP heat pump driven by fossil-generated electricity produces only marginally lower GHG emissions than a high-efficiency gas furnace. If the electricity is coal-generated, HEHP GHG emissions could actually be higher than a high-efficiency gas boiler. So, availability of renewable electricity, while not a barrier to HEHPs per se, is an impediment to achieving the ultimate objective – GHG emissions reduction.
- **Other electrical grid challenges.** Providing only 3% of space heating worldwide today, heat pumps have not had a major impact on the electric grid. Space cooling, on the other hand, already drives peak electricity demand in most of the US. So, substantial penetration of HEHPs worldwide would have major impact on the electric grid, increasing overall electricity demand and altering seasonal and diurnal peak loads for many utilities. For space cooling, a shift to higher efficiency heat pumps will *reduce* peak loads (which are highest in summer in most locations), but continued growth of space cooling demand could ultimately *increase* peak loads and stress grids in many

countries. Alternatives for addressing these impacts include active planning, demand management, and creative use of energy storage, electrical or thermal.

- **Refrigerant impact on GHG emissions**. In addition to indirect emissions through fossil fuel combustion for electricity generation, heat pumps contribute to GHG emissions through refrigerant leakage. Current refrigerants, in fact, have GWP thousands of times higher than CO_2. The world is moving to low-GWP refrigerants, but if the number of heat pump installations increases dramatically – many in places with limited maintenance capabilities – controlling refrigerant leakage will become a major challenge. There is reason for optimism: The Montreal Protocol has proven to be a successful framework for addressing previous ozone-depleting refrigerants (Goetzler, 2018, p. 57). But GWP is a major concern with such a vast scale up of vapor compression heat pumps.

1.2.4 Adoption Potential

A review of the literature makes it clear that high-efficiency heat pumps, using technology that is commercially available today, have the potential to dramatically reduce building energy consumption and GHG emissions.

A prime example is the IEA Energy Technology Perspectives 2017 report (IEA ETP, 2017), one of the most recent and most comprehensive prognostications of global future energy use and GHG emissions. IEA ETP forecasts are organized into 3 future scenarios: (IEA ETP, 2017, p. 23)

- **Reference Technology Scenario (RTS)**, which represents a major shift from a historical "business as usual" approach, requires significant changes in policy and technologies in the period to 2060 as well as substantial additional cuts in emissions thereafter.
- **2°C Scenario (2DS)**, which lays out an energy systems pathway and CO_2 emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100, represents a highly ambitious and challenging transformation of the global energy sector – substantially stronger than today's efforts.
- **Beyond 2°C Scenario (B2DS)**, which explores how far deployment of technologies already available or in the innovation pipeline can be pushed to take us beyond 2DS, is geared to achieving a 50% chance of limiting average future temperature increases to 1.75°C and 2060 energy sector emissions of net zero.

What do the IEA ETP scenarios forecast for HEHPs? Heat pump technology is projected to play a "vital role" over the next 40+ years, with performance increasing 250% to over 400%, helping to reduce 2060 building heating and cooling energy demand 32% in the 2DS scenario, and 45% in the more aggressive B2DS, compared with the RTS base case (IEA ETP, 2017, p. 130).

For space heating, in the base RTS scenario, final energy consumption is forecast to fall from 32% of 2014 total building energy use to 20% by 2060; the drop is partly due to building envelope improvements and partly a result of higher heat pump efficiency. In the 2DS scenario, where high-efficiency gas condensing boilers still play a big role, heating final energy is expected to drop to 18% of building energy use. In the aggressive B2DS case, where nearly all coal, oil and gas are eliminated from buildings, this fraction drops to 16% - only half of the 2014 ratio – and high-efficiency heat pumps with COPs of 4.0 to 4.5+ grow to comprise 47% of all installed space- and water-heating equipment, driven by MEPS of 150% (IEA HTP, 2017, p. 145, p. 157).

Spurred by growth in hot developing countries, space cooling is expected to grow from 5% of building final energy use in 2014 to 12% in 2060 in the RTS scenario. The HP final energy fraction is forecast to be only

10% in 2DS or B2DS – measured against a much-reduced energy basis. In the B2DS, case heat pump efficiencies are assumed to increase over 400% by 2060.

What do the IEA ETP scenarios say about the impact of high-efficiency heat pumps on final energy consumption and CO_2 emissions? Table 1.3 and Table 1.4 provide insights based on IEA ETP forecasts.

Table 1.3 Space cooling final energy consumption and CO2 emissions for 2014 and 2060 in IEA ETP RTS, 2DS, and B2DS

Building Space Cooling	RTS 2014	RTS 2060	2DS 2060	B2DS 2060
Final Energy Consumption (PJ)	5,978	20,184	13,047	11,687
Relative Final Energy Consumption (% RTS 2060)	N/A	N/A	65%	58%
Electric Heat Pump Adoption (%)	100%	100%	100.0%	100.0%
Emissions (MtCO2)	20	9	3	2
Relative Emissions (% RTS 2060)	N/A	N/A	32%	23%

Source: Calculation based on data from IEA ETP, 2017

Space cooling. Electrically driven vapor compression heat pumps, now and for the foreseeable future, provide 95+% of all space cooling. Table 1.3 summarizes global space cooling final energy consumption, electric heat pump adoption (which is close to 100%) and corresponding CO_2 emissions. As Table 1.3 shows, despite some building envelope efficiencies, cooling demand actually *increases* final energy consumption by almost 300% under the RTS scenario from 6,000 PJ in 2014 to over 20,000 PJ in 2060. In the 2DS and B2DS scenarios, 2060 final energy consumption is reduced to 65% and 58%, respectively, of the 2060 RTS value due to improved building envelope and increased heat pump efficiencies. CO_2 emission reductions are even larger, with 2060 emissions only 32% and 23% of the 2060 RTS value. There are three takeaways:

1. High-efficiency heat pumps (along with building envelope improvements) are a major factor to reducing final energy consumption by 35% to 42% below 2060 RTS energy consumption in the 2DS and B2DS scenarios – despite greatly increased cooling demand.
2. High adoption of HEHPs play a critical role in reducing 2060 GHG emissions by up to 77% from the 2060 RTS. And B2DS 2060 CO_2 emissions are only about 10% of 2014 emissions – despite a doubling in final energy demand.

3. "Greening" the grid plays a critical role in reducing CO_2 emissions. This is clear from Table 1.3 since 2060 GHG emissions are reduced far more than final (electricity) energy consumption in the 2DS and B2DS scenarios.

Table 1.4 Space heating final energy consumption and CO2 emissions for 2014 and 2060 in IEA ETP RTS, 2DS, and B2DS

Building Space Heating & Water Heating	RTS 2014	RTS 2060	2DS 2060	B2DS 2060	Relative Building Space Heating & Water Heating	2DS 2060	B2DS 2060
Final Energy Consumption (PJ)	62,746	61,773	48,241	38,543	Final Energy Consumption (% RTS 2060)	78%	62%
Heat Pump Adoption (%)	3%	7%	19%	47%	Heat Pump Adoption (%)	19%	47%
Emissions (MtCO2)	2,183	1,420	750	249	Emissions (% RTS 2060)	53%	18%

Source: Calculation based on data from IEA ETP, 2017

Space- and water-heating. Table 1.4 summarizes global combined space- and water-heating final energy consumption, electric heat pump adoption, and corresponding CO_2 emissions across IEA's three scenarios. In IEA's prognostication, heat pumps could increase their share of the installed building heating equipment base more than 15X, growing from 3% in 2014 to 7% in RTS 2060, to 19% in 2DS 2060, and to 47% in B2DS 2060. For the most aggressive B2DS case, this lowers 2060 final energy consumption to 62% of the RTS 2060 value (which is similar to RTS 2014) and reduces 2060 CO2 emissions to only 18% of RTS 2060 (only 12% of 2014 emissions). Important conclusions:

1. High-efficiency heat pumps (along with building envelope improvements) play a major role in reducing building heating final energy consumption in the 2DS and B2DS scenarios.
2. High adoption of HEHPs has a transformational impact on reducing GHG emissions that fossil-combustion space heating cannot match. The 2DS scenario, which still contains extensive primary fossil fuel combustion (albeit "high efficiency") has only 26% more energy consumption than B2DS, but almost 3X the CO_2 emissions of B2DS (where building fossil fuel is eliminated) in 2060.
3. As with space cooling, "greening" the grid plays an important role in reducing CO_2 emissions. This is clear since the reduction of 2060 GHG emissions between 2DS and B2DS (or between RTS and B2DS) is far greater than the final energy consumption reduction.

Table 1.5 summarizes the adoption potential for high efficiency heat pumps. IEA anticipates that heat pumps have the potential to grow to 47% of heating equipment building stock by 2060. Electrically driven heat pumps will continue to provide virtually all space conditioning, though IEA anticipates some penetration of non-vapor compression cycles and gas-powered units.

Table 1.5 Adoption Potential Summary for High-Efficiency Heat Pumps Using the B2DS Scenario

Building Application	2014 Heat Pump Adoption (%)	B2DS 2060 Heat Pump Adoption (%)	2060 Heat Pump Stock Efficiency (Wh/Wh)	Final Energy Consumption (% RTS 2060)	GHG Emissions (% RTS 2060)
Space Heating & Water Heating	3%	47%	4.0 to 4.5 Wh/Wh SCOP	62%	18%
Space Cooling	95%+	95%+	8.0 to 9.0 Wh/Wh SEER	58%	23%

Source: Based on data from IEA ETP, 2017; IEA Future of Cooling, p. 67 "Efficient Cooling Scenario", 2018

In 2060, IEA forecasts that virtually all new heat pumps will be high efficiency, with heating seasonal efficiencies on the range of 4.0 to 4.5 SCOP and cooling seasonal efficiencies of 8 to 9 SEER. These ranges are higher than the definition of "high efficiency" used in this report (3.5 heating SCOP and 5.9 cooling SEER) but are consistent with the highest efficiency heat pumps available today. So, achieving the potential forecast for HEHPs even 40 years in the future involves *application* of technology that already exists, not development of new technology.

IEA's result for both heating and cooling in 2060 show final energy consumption around 40% below the 2060 reference case and GHG emissions about 80% below the 2060 reference case.

This result is reasonably consistent with other earlier and higher-level forecasts of building energy efficiency. Urge-Vorsatz et al. (2012) in their "Deep Efficiency" scenario found a 34% reduction in building HVAC energy use between 2005 and 2050, which is pretty consistent with IEA ETP results for that timeframe. In their Global Energy Assessment, the International Institute for Applied Systems Analysis demonstrated that, with a somewhat more aggressive implementation of state-of-the-art building performance levels, a reduction of roughly 46% of 2005 global heating and cooling final energy use is possible by 2050 (IIASA GEA, 2012).

1.3 Advantages and Disadvantages of High-Efficiency Heat Pumps

1.3.1 Similar Solutions

HEHPs represent the only scalable and commercially proven in-building solution for reducing space heating and cooling GHG emissions for the next several decades.

Major competing solutions to high-efficiency heat pumps include:

- Fossil fuel combustion furnaces and boilers for space heating
- Electric resistance heating
- Fossil fuel-driven heat pumps
- Advanced non-vapor compression heat pumps
- District heating and cooling systems
- Solar heating and cooling systems

In terms of other high-efficiency alternatives: Modern district heating systems, primarily seen in European urban centers and on large campuses, can be very energy efficient with low GHG emissions if they use renewable energy, or draw on available "ambient" thermal energy sources (such as rivers, oceans, or warm sewage water) using central heat pumps. District heating and cooling (DHC) systems are limited to high energy density locations and to campuses with a single owner. For HEHPs, DHC systems represent both a partner and a competitor. Some of the most advanced high-efficiency DHC systems employ heat pumps for heat recovery (to boost ambient heat for space heating) and for temperature boosting to meet hot water needs (e.g., see Stanford Energy Systems Innovation webpage). But heat pump advocates sometimes view DHC as a competitor, especially when the DHC manager also controls electricity distribution (EHPA, 2014, p. 46, 73, 149, 150). Deciding between DHC and heat pumps – or a combination of the two – comes down to a detailed analysis of energy consumption, GHG emissions, and cost.

The other technologically-advanced alternatives to heat pumps – gas-fired heat pumps, new non-vapor compression cycles, and solar heating and cooling systems – all have small niches today. But, unlike air source heat pumps (ASHPs), they do not represent practical, scalable commercially available solutions today or in the foreseeable future.

1.3.2 Arguments for Adoption

High-efficiency heat pumps, driven by renewably generated electricity, represent a major vector for reducing GHG emissions. As quantified above, fossil fuel combustion for space heating is one of the greatest wastes of natural resources and one of the largest sources of GHG emissions in the world. HEHPs can easily deliver the low-quality energy needed, typically warm air or water at 50C to 80C, at efficiencies of 350%+ that fossil fuel combustion cannot match. HEHPs thus provide a low-risk, technically proven path for replacing fossil fuel-based space heating equipment, and dramatically reducing primary energy consumption and GHG emissions. In addition to their environmental advantages, air-source HEHPs also score high on the following practicalities:

- Applicability to every building type and size

- Applicability to almost all climates, possibly excepting very cold climates (some of which have employed ground-source heat pumps successfully, e.g., Sweden)
- Excellent life cycle economics
- Existing installation and operating expertise

1.3.3 Additional Benefits and Burdens

Additional benefits resulting for extensive implementation of high-efficiency heat pumps include:

- Reduced investment in fossil fuel-related infrastructure, especially natural gas transport and distribution, and in-house gas piping.
- Health benefits of reduced respiratory disease and fire risk, especially for buildings now heated by coal or wood.

Additional burdens and risks of HEHPs for space heating and cooling are:

- Where electricity is fossil generated, especially if by coal, growth of HEHPs could actually *increase* GHG emissions compared to high-efficiency gas furnaces and boilers.
- Widespread HEHP deployment could reduce energy source diversity and reduce resilience to a single point of failure, e.g., a grid outage. This suggests the need for decentralized generation and storage resources.

The availability of lower-cost, high efficiency space heating and cooling offers the risk of a "rebound" due to increased demand. This could occur in buildings that, for example, previously had inconvenient, inefficient space heating or no space cooling and now, with a heat pump installed, for the first time have efficient and cost-effective equipment. This could increase electricity demand beyond capacity, especially in developing countries where the grid is weak and powered by fossil fuel.

Table 1.6 compares HEHPs ("High efficiency heat pump"; ratings explained in Table 1.7) with other space heating and cooling alternatives in terms of breadth of application, GHG emissions, fossil energy reduction, cost, comfort and heath, and resilience. Compared with the "conventional" options that are common in developed countries (gas furnace and low-efficiency heat pump), HEHPs provide equivalent service and comfort across almost all building types, with far greater reduction of GHG emissions and lower life-cycle cost.

Compared with "Coal or wood combustion", HEHPs offer, in addition, higher breadth of application and much higher comfort, safety, and health. The one area of potential weakness is resilience due to complete dependence on the electric grid.

HEHPs, which can be installed in virtually any building, offer much broader breadth of application than district heating and cooling. But district heating and cooling, where available, can be a low cost and highly resilient option. The advanced options are at present high-cost niche alternatives.

Table 1.6 High-Efficiency Heat Pump Solution Comparison

Technology	Service (Heating / Cooling)	Breadth of Application	GHG Emissions Reduction	Fossil Energy Reduction	First Cost	Life Cycle Cost	Comfort and Health	Resilience
High-efficiency heat pump	Heating / Cooling	High	High	High	Medium to High	Low	High	Medium
Gas furnace	Heating	Medium	Low	Low	Medium	Medium	High	High
Coal or wood combustion	Heating	Low to Medium	Low	Low	Low	Medium	Low	High
Low-efficiency heat pump	Heating / Cooling	High	Low to Medium	Low to Medium	Medium	Medium	High	Medium-High
District heating and cooling	Heating / Cooling	Low	High	High	High	Low to Medium	High	High
Advanced heat pump cycles; Solar heating and cooling	Heating / Cooling	Low	High	High	High	High	High	High

Table 1.7 Ratings Key for High-Efficiency Heat Pump Solution Comparison

Level	Breadth of Application	GHG Emissions Reduction	Fossil Energy Reduction	First Cost	Life Cycle Cost	Comfort and Health	Resilience
High	67% to 100% of buildings	67% to 100%	67% to 100%	Top 1/3	Top 1/3	Top 1/3	Little or no risk of disruption
Medium	33% to 66% of buildings	33% to 66%	33% to 66%	Middle 1/3	Middle 1/3	Middle 1/3	Moderate risk of disruption
Low	0% to 33% of buildings	0% to 33%	0% to 33%	Bottom 1/3	Bottom 1/3	Bottom 1/3	Large risk of disruption

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) model which accounts for reductions in energy consumption and emissions generation for a solution relative to a conventional technology. 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, and for investment costing, adoptions are also converted to implementation units. The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment[2]) is what constituted the results.

The solution selected for this Technical Assessment is high-efficiency heat pumps (HEHPs) for space heating and cooling. The objective is to model the potential climate and financial impacts of a high adoption of high-efficiency heat pumps. The initial focus is on heat pumps for space heating; a high efficiency heat pump is defined as one with heating SCOP of at least 3.5 Wh/Wh.

[2] For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for; hence, net first cost results represent the period 2015-2050.

Table 2.1 summarizes the heating and cooling equipment that high-efficiency heat pumps are assumed to replace.

Table 2.1 High-efficiency heat pump replacement of conventional space heating and cooling equipment

Building Application	Conventional Equipment	HEHP Solution
Space Heating	• Combustion equipment including residential and commercial gas-fired and oil-fired boilers, furnaces and unit heaters. • Electric resistance furnaces and unit heaters.	High-efficiency heat pumps (SCOP of 3.5+ Wh/Wh), both central and room units: • Residential and commercial air-source heat pumps • Residential and commercial ground-source heat pumps
Space Cooling	• Low-efficiency residential and commercial air-source heat pumps and air conditioners, both central and room units.	High-efficiency heat pumps and air conditioners (SEER of 5.9+ Wh/Wh), both central and room units: • Residential and commercial air-source heat pumps and air conditioners • Residential and commercial ground-source heat pumps and air conditioners

The implementation unit is one *Heat Pump Installation Unit*. This unit of measure offers a clear representation of both the analytical implementation of the model as well as potential real-world applications of the model. For modeling purposes, this report analyzes both installation units for residential and commercial applications the same, as small distributed heat pumps (approximately 2-20 kW). Nevertheless, the total addressable market (TAM) and adoption analyses include all building sizes. This simplification is justified by observing the relative insensitivity of heat pump efficiency to unit size (with the possible exception of very large water-cooled chillers) as the Literature Review in Section 1 demonstrates.

In a departure from previous analyses, *delivered thermal energy* – either space heating or space cooling – has been selected as the *Functional Unit* of measure, consistent with other Project Drawdown building technology solution models. Delivered energy corresponds with the functional purpose of HEHPs – providing space heating or cooling comfort. Energy use is aggregated in terawatt hour therms (TWh (th)).

2.2 Data Sources

Primary sources for energy use and financial data, and data forecasts of conventional equipment and solution technologies, include assessments and studies from the International Energy Agency (IEA), the US Department of Energy (DOE) and the US Energy Information Agency (EIA), the European Heat Pump Association (EHPA), Lawrence Berkeley National Laboratory (LBNL), and International Renewable Energy Agency (IRENA). These data sources have been generalized to different regions using projections and other sources, primarily agencies like IEA for building energy use, and from there to space heating and cooling using Ürge-Vorsatz et. al. (2015). The results were aggregated for each equipment type to form the total first costs and energy use for each.

In most cases, US cost data have been used, as US costs are typically higher than elsewhere. This serves to form a conservative understated calculation of the net present value (NPV), as first costs are likely to be lower, and energy prices. and thus, operating cost savings, would likely be higher. A key underlying assumption in estimating adoption potential is that consumers will choose to install the most economically viable option. Often, this means switching to a more efficient version of their current equipment (such as from a low-efficiency gas furnace to a high-efficiency model) as changes to heat distribution, flue or other systems are typically very costly. However, it is usually easy to switch from a combustion furnace or room unit to an air-source heat pump, the primary solution modeled in the PDS scenarios.

Table 2.2 summarizes some of the most important data sources incorporated in this report:

Table 2.2 Key data sources incorporated in this update

Data Source	Significance
IEA (2017)	• Updated global data and scenario forecasts on building energy use, especially for space heating and cooling • Space heating equipment stock data and forecasts
US Department of Energy (2016)	• Data and forecasts on the air conditioning / heat pump market, including equipment efficiencies, costs, and technology • Review of new refrigerants, especially their global warming potential
IEA (2018)	• Updated global data and scenario forecasts on building space cooling needs, and heat pump / air conditioners efficiencies • Space cooling drivers, outlook, and policy directions
Zhao (2017)	• Data on China heat pump market trends and equipment for space heating, water heating, and space cooling

2.3 SPACE HEATING DELIVERED ENERGY TOTAL ADDRESSABLE MARKET (TAM)

With delivered energy as the functional unit, the space heating Total Addressable Market (TAM) is the total amount of thermal energy delivered for all residential and commercial building space heating worldwide.

Since data is widely available for space heating *final energy* (i.e., building consumption of natural gas, oil, electricity, etc.) from sources such as IEA or the US DOE, but much less so for *delivered energy*, space heating delivered energy from 2014 to 2060 was calculated as the product of final energy and space heating equipment efficiency, using historical data and future forecasts for both quantities (EIA, 2018; IEA ETP, 2017).

Table 2.3 presents the various fuels used to supply 2014 global residential and commercial space heating and the corresponding delivered energy TAM for each: (Drawdown Calculation based on IEA ETP 2017)

Table 2.3 2014 Space Heating TAM (Delivered Energy)

Energy Source	2014 Space Heating (TWh)	% TAM
Coal	673	7.4%
Oil products	1,258	13.8%
Natural gas	3,398	37.2%
Electricity	1,210	13.3%
Biomass, waste and other renewables	1,143	12.5%
Commercial heat	1,449	15.9%
	9,131	**100%**

Source: Drawdown Calculation based on IEA ETP, 2017

2014 delivered energy TAM is about 17% lower than final energy use. This is due to efficiencies below 100% for combustion-based space heating equipment, which provides the majority of heating final energy, compensated somewhat by electric heat pump efficiencies above 100%. The share of space heating delivered energy provided by electrical equipment, the 13.3% of the TAM, is ~76% resistance heating and 24% heat pumps. This space heating delivered energy calculation (2014 base year) was used as a proxy for delivered energy current adoption.

To forecast future delivered energy TAM, four TAM scenario forecasts were developed using a similar approach: "reference", "conservative, "ambitious", and "maximum". The 2014 to 2060 TAM forecasts vary only moderately across the four scenarios. Space heating delivered energy TAM is almost unchanged over the 46 years from 2014 to 2060 in the reference and conservative cases. In the ambitious and maximum cases, by contrast, space heating delivered energy *decreases* ~30% from 2014 to 2060, reflecting slow growth in space heating countered by building thermal envelope improvements to slowly reduce space heating delivered energy.

This calculation also considers switching between product classes, which is especially relevant for heat pumps where, due to the increased first cost of condensing furnaces and the substantially lower energy use of heat pumps (as well as space cooling benefit), there is projected to be substantial switching from fossil-fuel based furnaces to electric heat pumps.

This method considers residential and commercial new construction and replacement installations. This is necessary as installation costs and energy use vary greatly across scenarios. For each equipment type, this report treated these installations individually using representative installations and then aggregated them to form the total values for each equipment type.

2.4 Adoption Scenarios

Paralleling the TAM approach described above, the heat pump adoption analysis examined two different types of adoption scenarios: a baseline Reference Case (REF) and a set of Project Drawdown Scenarios (PDS) with varying levels of high-efficiency heat pump adoption. Published results compare each PDS to the REF, and thus focus on the *change* to the world relative to the REF baseline.

2.4.1 Reference Case / Current Adoption Scenario

The Reference Case assumes that the current relative proportions of space heating delivered energy for each fuel type, shown in Table 2.3, remain constant from 2014 to 2060. No major shift in technologies occurs; gas and oil furnaces and boilers, and low-efficiency electric heating equipment, continue to dominate the market.

2.4.2 Project Drawdown Space Heating Delivered Energy Adoption Scenarios

Three Project Drawdown scenarios (PDS) were developed to compare the impact of increased adoption of high-efficiency heat pumps to the Reference Case. The characteristics and 2014 to 2060 adoption levels of each scenario are summarized in Table 2.4.

Table 2.4 Summary of Project Drawdown Space Heating Adoption Scenarios

Variable	Reference Scenario	Plausible Scenario	Drawdown Scenario	Optimum Scenario
Scenario Type	Reference / Baseline	Realistically vigorous adoption	Optimized to achieve drawdown by 2050	HEHPs achieve maximum potential, fully replacing conventional technologies
Adoption Scope Modeled	All heat pumps	All heat pumps	All heat pumps	All heat pumps
2014 to 2060 HP Delivered Energy Adoption Growth	Constant HP share of delivered energy	Based on IEA ETP 2017 2DS	Based on IEA ETP 2017 B2DS	Based on Adoption Beyond IEA ETP 2017 B2DS
2014 HP Share of Delivered Energy (%)	3%	3%	3%	3%
2060 HP Share of Delivered Energy (%)	3%	25%	50%	60%
2014 Installed HP Average SCOP (Wh/Wh)	2.3	2.3	2.3	2.3
2014 to 2060 Installed HP Average SCOP (Wh/Wh)	2.3	3.1	3.3	3.6
2060 Installed HP Average SCOP (Wh/Wh)	2.3	3.9	4.3	4.5

Plausible Scenario

In the Plausible Scenario, high-efficiency heat pumps are adopted at a "realistically vigorous rate" from 2014 to 2060. Heat pump space heating delivered energy adoption grows from 3% of all space heating delivered energy in 2014 to 25% of TAM by 2060. In this scenario, the 2014-2060 installed HP average SCOP is 3.1, so on average a significant minority of installed heat pumps are "high efficiency" (SCOP = 3.5+) over this period. By around 2047, 50% of installed heat pumps are high efficiency, and in 2060, when installed HP average SCOP reaches 3.9, the bulk of installed heat pumps – and almost all heat pump sales – are "high efficiency" units.

Drawdown Scenario

In the Drawdown Scenario, high-efficiency heat pump adoption is optimized to achieve drawdown by 2050. In this case, based on the IEA ETP 2017 B2DS scenario, heat pump space heating delivered energy adoption grows from 3% of all space heating delivered energy in 2014 to 50% of TAM by 2060. And the 2014-2060 installed HP average SCOP is 3.3, so close to half of all installed heat pumps are "high efficiency" (SCOP = 3.5+) over this period. By around 2042, 50% of installed heat pumps are high efficiency, and in 2060, when installed HP average SCOP reaches 4.3, virtually all installed heat pumps – and all heat pump sales – are "high efficiency" units.

Optimum Scenario

In the Optimum Scenario, high-efficiency heat pump adoption achieves its maximum potential. HEHPs, along with renewable district heating and bioenergy, fully replace conventional space heating equipment. In this scenario, which is beyond the IEA ETP 2017 B2DS case, heat pump adoption grows from 3% of all space heating delivered energy in 2014 to 60% of TAM by 2060. After 2020, all heat pumps sold are high efficiency (SCOP = 3.5+) so that by 2033, 50% of installed heat pumps are "high efficiency", and by 2040 100% of installed heat pumps are high efficiency. In the Optimum Scenario, the 2014-2060 installed HP average SCOP is 3.6, so most installed heat pumps are "high efficiency" (SCOP = 3.5+) over this period. In 2060, the installed HP average SCOP reaches 4.5.

Adoption Scenario Modeling

The adoption forecasts developed in this Technical Assessment employed heat pump costs and emissions derived from implementation units of the current average conventional size used. Within each scenario, space heating delivered energy growth was modeled using Drawdown calculations based on IEA ETP 2017 final energy forecasts and EIA space heating equipment efficiency forecasts. Heat pump current adoption and adoption growth forecasts were based on IEA ETP 2017 final energy, emissions, and installed heating equipment forecasts (which include space- and water-heating) and other data and forecasts (EIA, 2018, EHPA, 2014). These data and forecasts provided enough triangulation across energy use, equipment adoption, and equipment efficiencies that it was not necessary to resort to diffusion models for the HP adoption forecasts.

2.5 INPUTS

2.5.1 Climate Inputs

The climate analysis in this model uses the values for energy intensity of space heating and reductions in energy consumption from heat pump usage (which are general "Technical" inputs in the Technical Inputs section). To calculate key model results, reported emissions factors for both electricity and fuel are used. Emissions factors for electricity generation are derived from the projected energy generation mix from three AMPERE RefPol scenarios in IPCC AR5 model Database (GEM3, IMAGE, MESSAGE) and the IEA's ETP 6DS scenario, and direct/indirect emissions factors by generation type taken from the IPCC AR5 Model Database, AMPERE3-MESSAGE Base scenario. The reader should note that since this combined reference projection includes a shift away from coal and oil to natural gas, the reference emissions factors decline slowly over the analysis period. Fuel emissions factors are calculated using the methodology recommended in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2, Annex 1. The values used are shown in Table 2.5.

To calculate the climate impacts of heat pump adoption in the PDS scenarios, estimations were made of the total reduction in both electricity and fuel consumption for space heating per TWh of space heating demanded. Emissions factors for grid electricity and fuel are applied to calculate maximum annual emissions reduction, total emissions reduction, and concentration change (in PPM equivalent). Then emissions reductions are calculated by applying the following equation for each year:

$$CO_2reduced = (Reduction\theta_{PDS}) \cdot (G_{ef}) + \sum_{each\ fuel} (Reduction\delta_{PDS}) \cdot (\mathrm{F}_{ef})$$

where:

- $CO_2reduced$ is the CO_2-eq emissions reduction associated with the reduction in energy consumption in each PDS scenario.
- $Reduction\theta_{PDS}$ is the reduction in energy consumption (TWh).
- G_{ef} is the emissions factor (in $t$$CO_2$-eq / TWh) of grid electricity globally for each year.
- $Reduction\delta_{PDS}$ is the reduction in fuel consumption (TJ) for space heating in each PDS scenario for each fuel.
- F_{ef} is the fuel emissions factor (in $t$$CO_2$-eq / TJ) for each fuel.

Updating of Grid Emissions Factors

As electricity sector Drawdown solutions are adopted, the grid becomes cleaner, and the high emissions factor shown in Table 2.5 will decline. This is not calculated directly in the model as it is considered an integration issue. This is dealt with in the Integration section of this report.

Table 2.5 Climate Inputs

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Global average REF Grid Emissions Factor	g CO_2e/kWh	503-593	Depends on year. Starts at High Input in 2020 & declines to Low Input in 2050 to represent the decarbonization of the grid in the reference.	12 each year	4
Combined REF Space Heating & Cooling Fuel Emissions Factor	t CO_2e/TJ of fuel	N/A	87.04	8 including individual fuel emissions factors and shares	1

Sources: IEA (2016) ETP, AMPERE Public Database (Version 1.0.0) https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB for Models: GEM-E3, IMAGE and MESSAGE

2.5.2 Financial Inputs

The first costs of heat pump and other HVAC equipment are equal to the sum of the retail price of the equipment and any material or labor costs necessary for installation. The reported installation costs for conventional and switch technologies are weighted residential and commercial applications. The source for these values comes from the DOE, EIA, IEA, and IRENA. These data are used to benchmark a published learning rate for comparable technologies at 9.61% (Taylor, 2013). Nonetheless, the installation costs for high efficiency heat pumps remain higher (weighted for residential and commercial applications) than conventional equipment. For many installations, first cost increases are mostly due to increased retail costs. For some, especially those going from baseline equipment to maximum efficiency equipment, the installation costs dominate the first cost calculation. The total first costs of all equipment shipped in the analysis period forms the total first cost for each equipment type. The total first costs of all equipment types for each scenario are then aggregated to form that scenario's total first costs.

The average annual use (i.e. TWh (th) per unit installed) is sourced primarily from Shah *et al* (2015), which presents estimates of residential and commercial HVAC usage for 12 countries representing a range of climate zones. Data is assumed consistent between the conventional and switch technologies.

Learning rate is from Taylor (2013), which evaluates the learning curve as it is related to regulatory impact analysis targeted at energy efficiency measures. The discount rate is sourced from several sources.

Table 2.6 and Table 2.7 show the model inputs used to calculate the financial costs and savings annually for heat pump adoption.

Table 2.6 Financial Inputs for the Conventional Technology

Variable	Unit	Full Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Installation Cost/ First Cost	US$2014/ unit	618-51,429	7,915	28	2
Annual Fixed Operating Cost	US$2014/ unit/ yr	38.62-2,221	280.32	12	1
Annual Fuel Cost	US$2014/ MWh (th)*	71.5	71.5	1	Derived from other inputs
Discount Rate for Future Cash flows	percent	3-15	5.37	20	9
Commercial Electricity Cost	US$2014/ kWh	0.0946	0.0946	838 (for 55 countries)	1
Residential Electricity Cost	US$2014/ kWh	0.139	0.139	509 (for 55 countries)	1

* The model actually uses kWh (th) for its financial inputs, but for ease of interpretation, the figures in this table are in MWh (th).

Table 2.7 Financial Inputs for the Solution Technology

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Installation Cost/ First Cost	US$2014/ unit	1,586-19,584	9,911	18	2
First Cost Learning Rate	percent	9.61%	9.61%	1	1
Annual Fixed Operating Cost	US$2014/ unit/ yr	19.32-299.40	115.09	6	1
Annual Fuel Cost	US$2014/ MWh (th)*	Approx. 40	~40; varies by HP SCOP	1	Derived from other inputs
Discount Rate for Future Cash flows	percent	3.0-15.0	5.37	20	9
Commercial Electricity Cost	US$2014/ kWh	0.0946	0.0946	838 (for 55 countries)	1
Residential Electricity Cost	US$2014/ kWh	0.139	0.139	509 (for 55 countries)	1

* The model actually uses kWh (th) for its financial inputs, but for ease of interpretation, the figures in this table are in MWh (th).

2.5.3 Technical Inputs

Besides strictly climate and financial inputs, several general variables were used in the analysis which had important impacts on both the climate and financial results. These are described in this section.

Energy Consumption and Efficiency Variables

It is assumed that for every TWh (thermal) produced by high-efficient heat pumps, an equivalent amount of energy would have been generated from conventional fuel combustion (coal, oil, and natural gas only)[3] and low-efficiency electric systems. While the replacement of these high-emissions technologies by electrical heat pumps will increase the overall usage of electricity, overall energy savings are achieved through reduced fuel combustion.

[3] Space heating from biomass is not considered to be replaced by high-efficient heat pumps in this study.

As discussed in the Literature Review, for conventional combustion-based heating systems, the maximum fuel to space heating delivered energy efficiency is 100%, while heat pumps, which *extract* heat from one location to supply heat to another, commonly achieve electrical energy to space heating delivered energy efficiency of 300% or greater. For this reason, it is important to carefully interpret energy efficiency metrics in order to accurately represent the situation, especially to distinguish between energy consumed (TWh) and energy supplied as heat (TWh (thermal) or TWh (th)).

A minor complication is that the conventional space heating energy sources include all the fuels named above plus electricity, but the solution – high-efficiency heat pumps – uses only electricity. The electricity consumed by the conventional technology is calculated by taking the fraction of the conventional energy sources provided by electricity as a fraction of all the conventional energy sources. This represents the average TWh of electricity used for each TWh (th) supplied. Similarly, the fuel energy consumed is taken as the remaining energy consumed converted to TJ (the fuel energy input unit).

The solution only uses electricity, and the amount of electricity is based on the seasonal coefficient of performance (SCOP) which indicates how much electricity will be is needed for each TWh (th) supplied. This is simply the inverse, 1/SCOP. Input variables are shown in Table 2.8.

Lifetime Variables

Several additional variables were necessary to calculate the financial benefits of installing high efficiency heat pumps. These include estimates for the life expectancy of both conventional as well as solution technologies. Though life expectancies for these technologies can vary considerably based on numerous factors, the model uses data from several sources including the IEA's Energy Technology System Analysis Programme (ETSAP), the International Renewable Energy Agency (IRENA), the US Department of Energy (DOE) and the Lawrence Berkeley National Laboratories (LBNL). These data are mostly in years of life (for the lifetime) and in hours per day (for the usage). These were converted to energy output using the average technology size variables (in kW).

The average annual use was calculated by assuming 365 days of use at the average hours of use per day obtained from the sources, and this total annual usage in hours was converted to an energy output by multiplying by the system size.

The lifetime capacity for each technology was collected mostly in years and converted to total energy output by multiplying the average number of years by the energy output per year. The variables are shown in Table 2.9.

Table 2.8 Technical model inputs for Energy Consumption and Efficiency

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data-points (#)	Sources (#)
Electricity Consumed for Conventional Building Heating*	TWh/ TWh(th)	0.185	0.185	1	Derived from other inputs
Average Electricity Consumed for Solution Building Heating*	TWh/ TWh(th)	Varies: 1/(Average SCOP between 2014 and 2060)	0.278 to 0.345, depends on average SCOP (2.9 to 3.6)	16	9
Fuel consumed by Conventional Commercial Building *	TJ/ TWh(th)	2,933.6	2,933.6	1	Derived from other inputs
Fuel Consumption reduction Solution Compared to Conventional	percent	100%	100%	1	Assumed by Project Drawdown
High Efficiency Heat Pump SCOP	TWh (th) / TWh	2.5-4.1	3.5 minimum for space heating	16	9

* Per unit *delivered energy*

Table 2.9 Technical model inputs for Usage and Lifetime

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data-points (#)	Sources (#)
Lifetime Capacity of conventional technology	MWh(th) per Implementation Unit*	944-1,870	1,410	13	2
Average Annual Use of conventional technology	MWh(th) per Implementation Unit	12.3-118	65.2	29	3
Lifetime Capacity of solution technology	MWh(th) per Implementation Unit	600-1,410	1,000	18	8
Average Annual Use of solution technology	MWh(th) per Implementation Unit	2.02-113	52.6	26	2
Average Conventional Technology Size (Weighted Residential and Commercial)	kW	1.03-234	42.16	16	1
Average Residential Heat Pump Size	kW	2-19	7.68	10	2
Average Commercial Heat Pump Size	kW	14-10,551	513.24	10	2

* The model actually uses TWh (th) for its energy inputs, but for ease of interpretation, the figures in this table are in MWh (th).

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 1. the infrastructure required for the solution is available and in-place, 2. policies required are already in-place, 3. no carbon price is modeled, 4. all costs accrue at the level of agency modeled, 5. improvements in technology are not modeled, and 6. that first costs may change according to learning. Full details of core assumptions and methodology are available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: Heat Pumps replace only coal, oil, gas and electricity-based conventional space heating/cooling (that is, not biomass, renewables, nor commercial heat).

Assumption 2: Only electricity-powered heat pumps are modeled as they use no direct fuel and get cleaner as the grid gets cleaner.

Assumption 3: The vast majority of current electricity-based space heaters are inefficient heaters that can be replaced by high efficiency heat pumps.

Assumption 4: Indirect emissions are not critical in this analysis (lack of data).

Assumption 5: Major published forecasts (IEA, USDOE, EIA, and others) of final energy, equipment efficiencies, especially heat pumps, and installed equipment shares are valid and self-consistent.

Assumption 6: "Installed heating equipment" share forecasts are proportional to delivered energy share for heat pumps and other equipment.

Assumption 7: Future evolution of building space heating final energy and delivered energy, and space heating equipment efficiencies and adoption shares are all smooth enough for linear interpolation to be valid.

2.7 Integration

The complete Project Drawdown integration documentation (available at www.drawdown.org) details how all solution models in each sector are integrated, and how sectors are integrated to form a complete system. 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.

Each solution in the Buildings and Cities Sector was modeled individually, and then integration was performed to ensure consistency across the sector and with the other sectors. These solutions require an integration analysis to avoid double counting, as they primarily relate to either reducing demand for space heating and cooling (for residential and/or commercial buildings), commercial lighting, cooking, or water heating. The integration process, therefore, was addressed through sequential adjustments to the efficiencies of the solutions in four separate sequence chains: 1. space heating and cooling, 2. lighting, 3. cooking, and 4. water heating. The prioritized sequence is fixed for all scenarios and is described in the Drawdown Building Sector Integration documentation.

For each solution in an integration sequence, the estimated impact of previous solutions on the emissions savings of the current solution is estimated and a reduction factor is applied. The factor is only applied to emissions and energy savings attributed to adoptions that overlap with previous solutions[4], and for this

[4] This can be interpreted as a single building with multiple efficiency technologies.

adoptions are generally assumed independent. Solutions that start each integration sequence are therefore unaffected (unless they are affected by solutions in other sequences), and solutions that apply to different buildings (say commercial and residential) do not affect each other. The method of estimating overlap is based on the percent adoption of the higher priority solution applied to the area adopted in the lower priority solution. For the efficiency factor of this overlapping area only, 1. the reduction factor is applied, 2. the reduced efficiency factor is scaled so that it can be applied to all adoption units in the solution model while accurately estimating adjusted total saving, and 3. used to update the results in the lower priority solution model.

As Heat Pumps directly replaces TWh of heating provided by conventional means, uses TWh (th) as the functional unit not floor area, and its adoption did not exceed the total building space energy demand, no adjustment was necessary for integration.

In addition to the building sector integration, there was an integration process across the grid and electricity efficiency solutions (buildings, transport, materials etc.) which adjusted for double counting. Double counting of emissions reduction was a factor of using the reference grid emissions factors for electricity-based solutions. As grid solutions (Utility-scale Solar PV and others) are adopted, the grid gets cleaner and the impact of efficiency solutions is reduced (where they reduce electricity demand) or increased (where they increase electricity demand[5]). Grid solutions are adjusted to remove the double counting as described in the Project Drawdown integration documentation.

2.8 LIMITATIONS/FURTHER DEVELOPMENT

One limitation is that the impacts of high-efficiency heat pumps on space heating energy consumption and GHG emissions reported in this Technical Assessment are limited to impacts at the *building level*. But, as discussed in the Literature Review, HEHPs provide two benefits:

- Reducing building energy consumption.
- Supporting the replacement of building fossil fuel energy consumption with renewably generated electricity. It is clear that this impact can be large if the grid shifts to renewable electricity (IEA ETP, 2017).

So, this Technical Report addresses only the first benefit in depth.

In terms of further development, in conducting an analysis of equipment such as HEHPs, it is essential that the analysis be self-consistent in terms of the relationship between equipment efficiency, equipment

[5] Some solutions such as Electric Vehicles and High-Speed Rail increase the demand for electricity and reduce the demand for fuel.

adoption, delivered energy TAM, and the broader scenario "world" – all of which are time dependent. The current RRS model supports a single heat pump SCOP, so it is necessary to conduct analysis runs using an approximate "average" heat pump SCOP (and static fossil heating equipment efficiencies). This was compensated by using time-varying efficiencies in calculating delivered energy from final energy forecasts. A valuable improvement for further development would be more dynamic time-dependent HVAC efficiencies throughout.

3 RESULTS

3.1 ADOPTION

Table 3.1 presents the world adoptions of heat pumps and high-efficiency heat pumps in some key years of analysis in functional units and percent, as well as 2050 heat pump installed SCOP, for the three Project Drawdown scenarios.

Table 3.1 World Adoption of the Solution

Solution	Units	Base Year (2014)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Heat Pumps	*TWh (th) Delivered Energy*	290	1,448	2,770	3,314
	% TAM	3.2%	20.3%	39.8%	47.6%
Heat Pump Average Installed SCOP	*Wh/Wh*	2.30	3.55	3.87	4.25

Figure 3.1 presents the world adoptions of heat pumps in functional units for the three Project Drawdown scenarios.

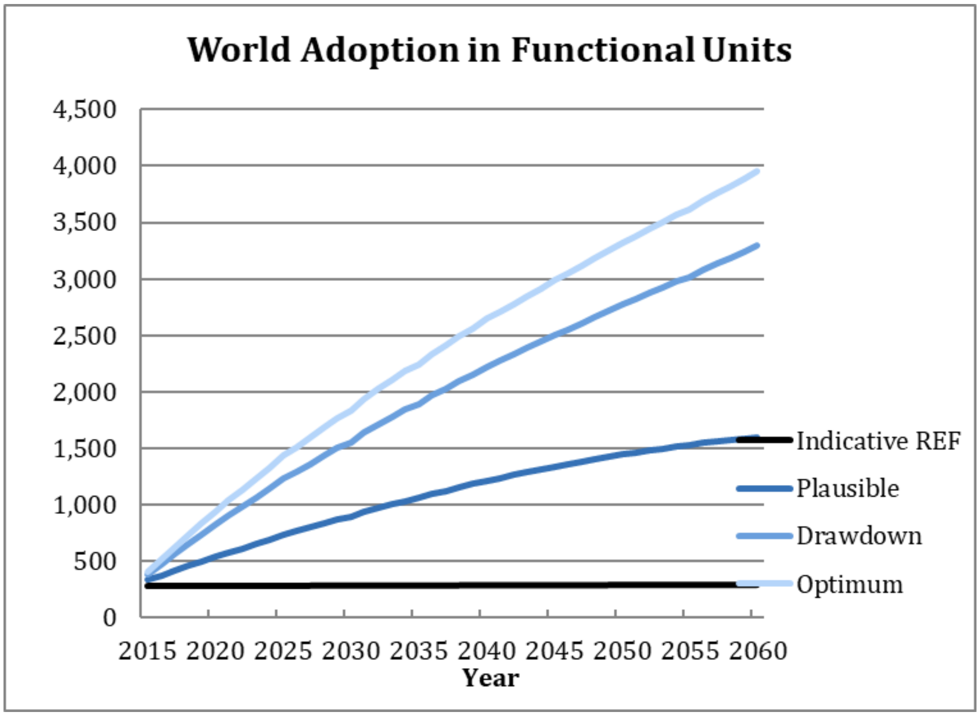

Figure 3.1 World Annual Adoption 2020-2050 in Functional Units (TWh (th))

Figure 3.2 presents the world adoptions of heat pumps as a percent of TAM for the three Project Drawdown scenarios.

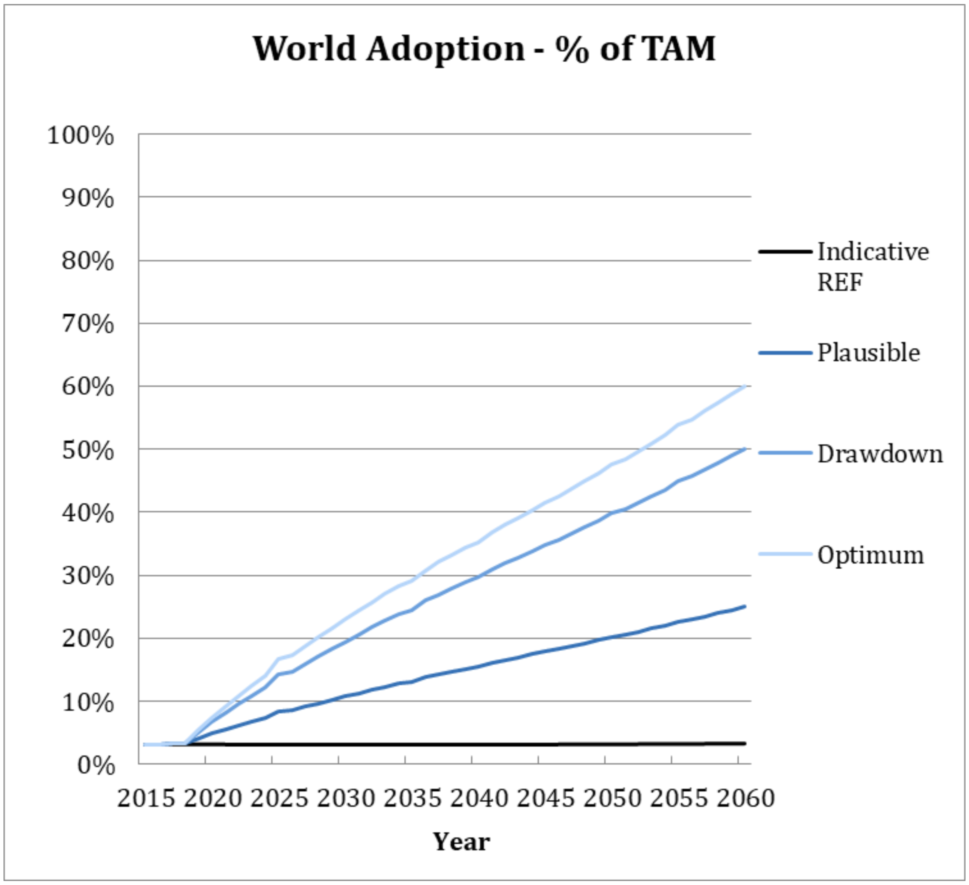

Figure 3.2 World Annual Adoption 2020-2050 % of TAM

3.2 Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the Glossary Section.

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq/yr. (2020-2050)*	(Gt CO_2-eq/year)	*(Gt CO_2-eq/year)*
Plausible	0.21	4.19	0.11	0.21

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq/yr. (2020-2050)*	(Gt CO_2-eq/year)	*(Gt CO_2-eq/year)*
Drawdown	0.49	9.39	0.24	0.49
Optimum	0.63	12.20	0.31	0.63

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).

Table 3.3 Impacts on Atmospheric Concentrations of CO_2-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO_2-eq (2050)	*PPM CO_2-eq change from 2049-2050*
Plausible	0.35	0.02
Drawdown	0.77	0.04
Optimum	1.00	0.05

Figure 3.3 presents the world GHG emissions reductions as a result of heat pump adoption for the three Project Drawdown scenarios.

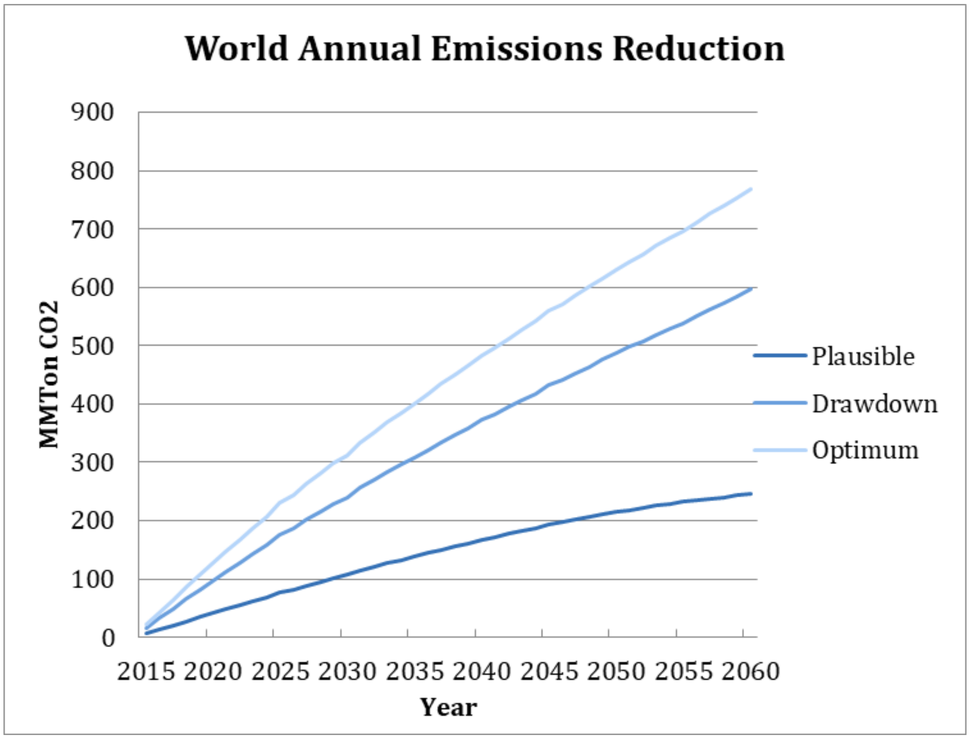

Figure 3.3 World Annual Greenhouse Gas Emissions Reduction

3.3 Financial Impacts

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary.

Table 3.4 Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Cost Savings	Lifetime Operating Cost Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	283.79	82.80	738.14	1,085.08	246.34
Drawdown	570.78	140.87	1,683.98	2,494.49	583.49
Optimum	685.87	161.42	2,229.62	3,303.25	783.17

Figure 3.4 presents the world operating cost reductions for the three Project Drawdown scenarios.

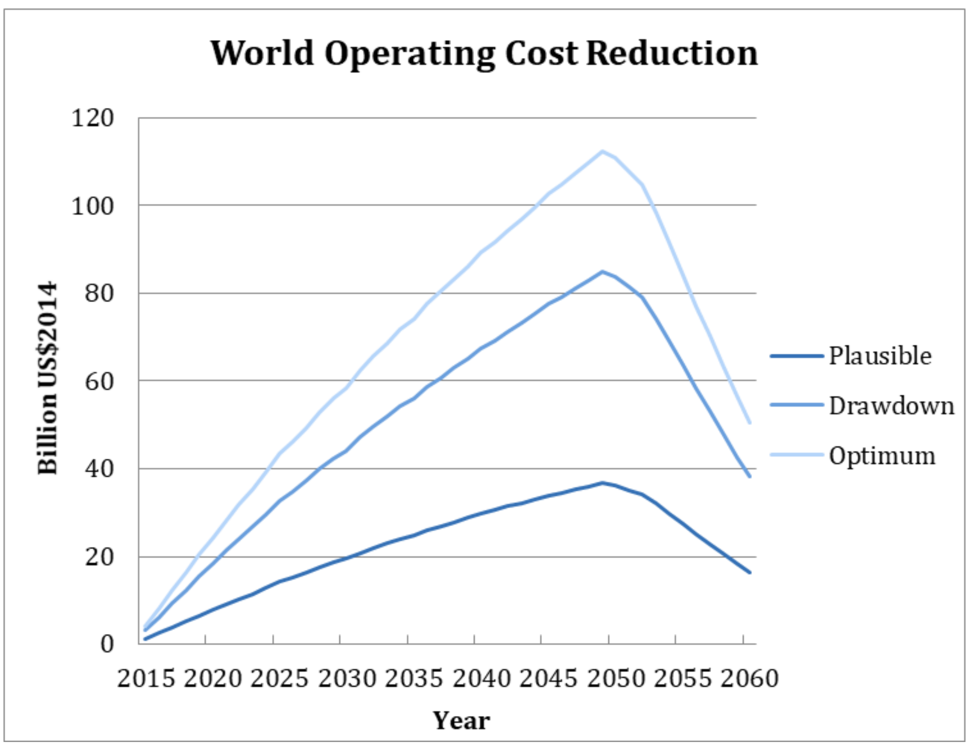

Figure 3.4 World Net Operating Cost Reductions Over Time

3.4 Other Impacts

As discussed in the Literature Review, HEHPs for space heating can reduce CO_2 emissions in two ways:

1. Increasing space heating energy efficiency, thus reducing building fossil fuel and electricity use.
2. Replacing onsite fuel use with renewably generated electricity.

Results presented in this report, including a reduction in CO_2 emissions of up to 12 Gt CO_2 between 2020 and 2050 in the Optimum Scenario, are based on in-building benefits – increased space heating energy efficiency.

But what is the magnitude of the impact of using heat pumps for building space heating *and* shifting the electric grid to use renewably generated electricity? Drawdown estimates these impacts by calculating the net reduction in emissions due to all solutions and forecast grid technologies. The result is additional 2020-2050 emissions reductions of approximately 1 to 3 Gt CO_2-equivalent, depending on scenario.

4 Discussion

High-efficiency heat pumps (HEHPs) offer a low-risk, technically-proven path for reducing GHG emissions in one of the world's largest and most carbon-intensive energy sectors – building space heating. Along with electric vehicles, and electrification of other energy end uses, HEHPs represent a major part of the CO_2 Drawdown solution: accomplish the function electrically, provide the electricity renewably.

High-efficiency heat pumps, if widely adopted, could provide 48% of building space heating delivered energy by 2050 and 60% by 2060. The result of the Project Drawdown 'Drawdown' Scenario, with 39.8% HEHP adoption in 2050, would be a reduction of 9.39 Gt of 2020-2050 CO_2 emissions compared with the Reference Scenario. This would reduce atmospheric GHG concentration by 0.77 PPM CO_2-equivalent in 2050. Lifetime operating cost savings would total $2.49T from 2020 to 2050, with a lifetime cash flow savings NPV of $0.58T. Applying HEHPs to building space cooling could deliver similar scale benefits.

High-efficiency heat pumps can have widespread and cost-effective application: Air-source heat pumps can be installed virtually anywhere in new construction and usually can be retrofitted into existing buildings. Heat pumps that meet the definition of high efficiency – seasonal coefficient of performance (SCOP) of 3.5 or greater – are commercially available today. And 2060 installed heat pump efficiencies are expected to average up to 4.0 to 4.5 or greater SCOP.

Yet, in 2014 heat pumps provided only about 3% of space heating delivered energy worldwide. And high-efficiency heat pumps provided less than 1%.

What are the barriers and what needs to be done?

Some of the key barriers and challenges to future adoption and full emissions impact of HEHPs for space heating include:

- Competition against low-cost CO_2-emitting fossil fuels.
- Relatively high HEHP first cost compared with other space heating equipment.
- Reduced efficiency and capacity in very cold weather.
- Obtaining sufficient renewably generated electricity.
- Addressing electrical grid changes due to large-scale adoption of HEHPs, such as increased overall demand and altered peak loads for many utilities.
- Increased potential for refrigerant leakage contributions to GHG emissions (though the world is moving to low-GWP refrigerants, leakage could be a major concern with such a vast scale up).

Key success factors, proven in the past, and needed to accelerate future HEHP global adoption include:

1. Government policies at international, national, and local levels, incorporating:
   - A clear vision of energy consumption / GHG emissions objectives and strategy
   - Increasingly high HP minimum performance and renewable content standards (MEPS)
   - Financial incentives for preferred HEHP system installations to help buyers consider, not only first cost, but also future operating cost (50% to 80+% of lifecycle HEHP cost)
   - Accurate comparative labeling supported by relevant seasonal performance and cost metrics
2. Heat pump industry collaboration with other industries, academia, and government
3. Utility energy efficiency programs and incentives
4. Ongoing heat pump technological improvement and cost reduction, especially:
   - Expanded employment of efficiency improvements that already exist in many commercial high-efficiency units
   - Improved efficiency and capacity at very low outdoor temperatures.
5. Integrated framework including:
   - Government policies as outlined above
   - Support for HP R&D
   - Industry-government collaboration
   - Investment prioritization, especially to avoid fossil fuel-related stranded asset investment

4.1 Limitations

Electrically powered vapor compression heat pumps, as a modular space heating solution that is already ubiquitous, face few limitations. Technically, the biggest limit on the widespread adoption of high-efficiency heat pumps is low efficiency and low capacity (which translates to high cost) at very low ambient temperatures. And this is an active research topic as noted in the Literature Review.

Financially, the main limitation on widespread HEHP adoption is cost. Though high-efficiency heat pumps are commercially available, most heat pump sales are units with efficiency just above MEPS requirements (Lapsa, 2017). The modifications that increase HP efficiency – variable frequency drives, multi-compressor units, larger heat exchangers, more aerodynamic fans, etc. – add first cost. Even though, this Marginal First Cost increment ($140B worldwide in the Drawdown adoption scenario) is more than offset by Lifetime Operating Cost Savings ($2,494B in Drawdown adoption), most heat pumps sold just meet the minimum standards.

Environmentally, HEHPs can contribute to a major reduction in direct GHG emissions by eliminating fossil fuels from space heating, as quantified above. Indirect GHG emissions of the HEHP equipment itself can be expected to be somewhat higher than fossil fuel equipment, roughly in proportion to unit cost, since the equipment is pretty similar to the mechanical space heating equipment that HEHPs replace. One potential exception and concern, as quantified above, is emissions from refrigerant leakage.

Moving into the future, rapid growth of HEHPs without adequate planning could be in some ways "self-limiting". HEHPs, if they are to reduce GHG emissions, require renewably generated electricity. Growth from 3% of space heating today to 60% in 2060 would represent a major additional load for the electrical grid in many places. And it could reduce resilience and create risk of failure by reducing the diversity of space heating primary energy sources.

4.2 BENCHMARKS

The IEA Energy Technology Perspectives reports offer well-know, well-documented benchmarks. Table 4.1 compares IEA 2020-2050 space heating emissions reduction and 2050 heat pump adoption forecasts with the results of Drawdown modeling. IEA B2DS 2050 HP adoption (42.8%) is intermediate between the Drawdown (39.8%) and Optimum (47.6%) adoption scenarios. (Note that IEA ETP HP adoption includes both space and water heating.)

Table 4.1 Benchmarks

Source and Scenario	Total Emissions Reduction (*Gt CO_2-eq 2020-2050*)	2050Adoption (% of TAM)
IEA ETP 2017 B2DS vs. RTS Scenarios	19.6	42.8%*
IEA ETP 2016 2DS vs. 6DS Scenarios	19.5	N/A
Project Drawdown – Plausible Scenario (PDS1)	4.2	20.3%
Project Drawdown – Drawdown Scenario (PDS2)	9.4	39.8%
Project Drawdown – Optimum Scenario (PDS3)	12.2	47.6%

Source: IEA (2017) ETP, IEA (2016) ETP
*"% of installed heating equipment", both space and water heating

IEA ETP emissions reductions from 2020 to 2050, a total of 19.6 Gt CO2-eq from 2020 to 2050 for IEA's B2DS scenario in comparison with its RTS scenario, are comparable but significantly larger than the 9.4 Gt reduction in the Drawdown scenario, which is closest to B2DS, and 12.2 Gt reduction in Drawdown's Optimum scenario. Key reasons for this difference are:

- IEA includes emissions reduction from applying heat pumps to water heating; Drawdown does not.
- IEA includes grid impacts in its HP emissions figure; Drawdown tracks these separately.
- IEA assumes in its 2DS and B2DS scenarios significant “negative emissions” from biomass combustion coupled with carbon capture and storage (CCS) (Dulac, 2019); Drawdown does not.

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6 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 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 high growth of the solution.

Approximate PPM Equivalent – the reduction in atmospheric concentration of CO_2 (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, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. Global weighted averages for this input are 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 over the lifetime 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 CO_2e/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 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 provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experience 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 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 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 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**.

Total Emissions Reduction – the sum of 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.

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