

TECHNICAL ASSESSMENT FOR DISTRICT HEATING SYSTEM

SECTOR: BUILDINGS AND CITIES

AGENCY LEVEL: COMMUNITY

KEYWORDS: DISTRICT HEATING SYSTEM, COMBINED HEAT
AND POWER, COGENERATION SYSTEM, SPACE AND WATER
HEATING EFFICIENCY, ENERGY SAVING, BUILDING
ENERGY SAVING

BOOK EDITION 1

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Suggested citation

Allard, R. Metz, P., Toroghi, S., Herbert, Y., & Frischmann C.J (2022). District Heating. Project Drawdown

*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

- B2DS – 2 degree C Scenario (IEA ETP 2017)
- CCS – Carbon capture and storage
- CHP – Combined Heat and Power
- DH – District Heating
- DOE – US Department of Energy
- EIA – Energy Information Agency (US DOE)
- ESTAP – Energy Technology Systems Analysis Program
- GHG – Greenhouse gas
- GIS – Geographical information system
- GWP – Global warming potential
- HRE – Heat Roadmap Europe
- HVAC – Heating, ventilating and air conditioning
- IEA – International Energy Agency
- IEA ETP – International Energy Agency Energy Technology Perspectives Report
- IEA WEB – International Energy Agency World Energy Balances
- IPCC – Intergovernmental Panel on Climate Change
- IRENA – International Renewable Energy Agency
- kW – kilowatt
- kWh – kilowatt hour
- LBNL – Lawrence Berkeley National Laboratory
- MSW – Municipal solid waste
- NPV – Net present value
- PDS – Project Drawdown Scenario
- RDH – Renewable District Heating
- REF – Project Drawdown Reference Scenario
- RTS – Reference Technology Scenario (IEA ETP 2017)
- TAM – Total available market
- TW – Terawatt
- TWh – Terawatt hour
- 2DS – 2 degrees C Scenario (IEA ETP 2017)
- WTE – Waste to energy

EXECUTIVE SUMMARY

Globally, the building and construction sectors emit 39% of all energy-related CO₂ and consume 36% of the world's annual energy. There is, therefore, an acute need for solutions to reduce building energy consumption and emissions across building energy end-uses.

Renewable District Heating (RDH) offers unique potential for reducing GHG emissions by replacing individual fossil-fueled in-building space heating equipment with a community-based system using local renewable energy resources that are not accessible to individual buildings.

Thus, RDH provides an important path for reducing GHG emissions in one of the world's largest and most carbon-intensive energy sectors – building space heating. Widely adopted, beyond its current 2% adoption, RDH could provide over 20% of building space heating delivered energy by 2060. The result, detailed in Project Drawdown “*Drawdown*” Scenario, would be a reduction of 9.8 Gt of 2020-2050 CO₂ emissions compared with the Reference Scenario. This would reduce atmospheric GHG concentration by 0.83 PPM CO₂-equivalent in 2050. Lifetime operating cost savings would total \$2.4T from 2020 to 2050, with a lifetime cash flow savings NPV of \$0.28T. Applying RDH to building water heating could deliver similar scale benefits.

But today, fossil fuel provides over 90% of all DH energy. And RDH faces key challenges and barriers:

- Competition from low-cost CO₂-emitting fossil fuels and from high-efficiency HVAC equipment.
- Limitation of District Heating to high energy-density urban areas.
- High first cost and need for a community energy “utility” requiring in-ground installation.
- Shrinking space heating loads, decreasing energy density, as building thermal envelopes improve.
- Need for coordination with other energy resources, especially with the electrical grid and with municipally-controlled energy resources, such as municipal solid waste.

Despite these challenges, Scandinavian experience over the last 40 years clearly demonstrates that it is possible to economically convert DH networks to renewable energy. And “high-density” is not a fixed number; the threshold for DH application can be expanded through innovation and suitable energy strategy and policy. Key success factors needed to realize the unique potential of Renewable District Heating include:

- Integrated energy strategy and government policies on energy consumption and GHG emissions.
- High energy density heating loads, depending on the policies that are implemented.

- Ongoing Renewable District Heating technological innovation and implementation, especially advancement of low-temperature (~50C) distribution networks, CHP plants based on municipal solid waste and biomass, and central heat pump-boosted “ambient energy” sources.

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 CO₂ 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 were 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 by light technology and use.

1.1 STATE OF DISTRICT HEATING

1.1.1 What is District Heating?

District Heating (DH) is a community-scale space-heating system that uses local fuel or heat resources that would otherwise be wasted, delivered by a distribution network of pipes, to heat buildings (Werner, International review of district heating and cooling, 2017, p. 618). To establish and operate a DH system, a community needs to procure suitable heat sources, build and operate the distribution network, and install heat exchangers in each building served. Implicit is long-term commitment of community-scale heat resources and for building owners to purchase heat from the DH system. So, government involvement is essential (unless the system has a single private owner, such as a university campus, hospital complex, or large industrial plant).

1.1.2 Potential Impact of District Heating

District heating offers unique potential for reducing GHG emissions by replacing individual fossil-fueled boilers and furnaces, and fossil-generated electric heat, with available local heat resources that are not well-suited for, or not available to, individual buildings. These include:

- “Recycled heat”, such as reject heat from combined heat and power (CHP) (cogeneration) plants, which may be fired by fossil fuel or biomass.
- Recycled heat from waste-to-energy (WTE) plants or from industrial process heat.
- Renewable heat resources, such as biomass, geothermal, and large-scale solar thermal energy.
- “Ambient heat” from sewage waste streams, rivers, and oceans, thermally upgraded by central heat pumps.

By utilizing local energy resources that would otherwise be wasted, DH systems have a unique “economy of scope” niche among energy systems (ibid), and, thus, offer unique future potential – in the right circumstances as delineated below – as a low-cost space heating solution that significantly reduces GHG emissions (Connolly, 2014).

1.1.3 District Heating Evolution – Past, Present and Future

Although the basic concept of district heating has not changed in over 100 years, the drivers for district heating and best-practice implementation have evolved, especially over the last few decades as GHG emissions reduction has become a top driver. Table 1.1 summarizes the four “generations” of district heating systems:

Table 1.1 District Heating evolution and drivers

Generation	Driving Issues	Character	Heat Source	Heat Supply Vector	Supply Temperature (C)	Return Temperature (C)
1 st Generation (1880-1930)	First DH “best-available” technology based on Birdsill Holly designs	Fossil-fueled boilers; steam system with steam pipes, condensate return	Coal	Steam	215	200
2 nd Generation (1930-1980)	First European commercial systems; best-available technology	Large “build on site” stations; boilers and co-generation	Coal, natural gas, oil	Pressurized hot water	120	70
3 rd Generation (1980-2020)	International oil crisis; energy independence	“Scandinavian system”; pre-insulated pipes; industrialized compact substations	Increased use of biomass and industrial “waste heat”	Hot water	90	40

Generation	Driving Issues	Character	Heat Source	Heat Supply Vector	Supply Temperature (C)	Return Temperature (C)
4 th Generation (2020-2050) [proposed]	Reducing CO ₂ emissions to address change; leveraging networking and building envelope advances	Low energy demand; “smart energy” management of sources, distribution and consumption	Increased use of renewable energy, “recycled heat”, and “ambient heat” resources	Warm water	50 to 70	20 to 40

(Source: Lund, 2014; Averfalk, 2017; Lund, 2018)

As Table 1.1 illustrates, from 1880 until today, the top energy issues of the day have driven District Heating evolution. The initial challenge, typical of 1st and 2nd Generation DH, was simply utilizing the best heat generation and delivery technology available. In the 1970s the focus changed – especially in oil-short Scandinavia – which developed 3rd Generation DH to address the international oil crisis. And today, proposed 4th generation DH systems seek to address climate change by reducing GHG emissions dramatically.

DH heat sources have evolved correspondingly, at least in Europe. 1st Generation DH systems were based on fossil-fueled boilers. 2nd Generation DH systems increasingly used more energy-efficient, less-polluting CHP systems, still fired by fossil fuel, to provide both electricity and heat. 3rd Generation DH, spawned in oil-poor but forest-rich Sweden, and other Scandinavian countries, in response to the oil crisis of the 1970s, increased the adoption of CHP and shifted the primary fuel increasingly to biomass and local “waste heat” of various types (Ericsson and Werner, 2016).

By contrast, DH heat sources in Russia and China, even today, are roughly a 50/50 mix of boilers and CHP generators. Russia fires its DH systems predominately with natural gas and, as of 2010, coal-fired boilers and CHP plants provided over 90% of northern China’s DH supply (Werner, 2017; Gong & Werner, 2014, p.30).

The distribution network, the number-one differentiator of DH in comparison to individual building space heating, has likewise evolved. To cut costs and reduce distribution piping thermal losses, supply temperatures have dropped over the years from 200+C steam in early systems, to 90C hot water in 3rd Generation systems. Modern distribution networks also incorporate cost-cutting design and manufacturing efficiencies, such as prefabricated, pre-insulated piping, and prefabricated substations.

Proposed 4th Generation District Heating, which represents both a continuation of and a departure from this long evolution, seeks to connect increasingly diverse and fluctuating renewable and waste heat energy sources with increasingly energy-efficient buildings. Advocating supply temperatures as low as

50C with return temperatures as low as 20C, 4th Generation DH backers seek to address several key success factors: (Lund, 2018)

- Serve the needs for space heating (and water heating) of increasingly energy-efficient buildings.
- Distribute heat with low grid losses.
- Recycle heat from a range of low-temperature “waste heat” and “ambient heat” sources.
- Integrate renewable sources such as solar and geothermal.
- Operate as part of a “smart energy system” in order to seamlessly integrate fluctuating renewable energy sources (supply side) while addressing building energy conservation.
- Ensure that the requisite planning, incentive structures, and strategic investments needed to deliver future sustainable energy systems are in place.

1.1.4 Key Success Factors

Specific success factors will be addressed within the context of two national case examples in “Current Adoption” below. But several broad success factors are apparent:

- **Government strategy and policy.** Preeminently, most major public DH systems in the world have had strong government energy strategy, backed by DH mandates and customer incentives, to guarantee a heating load, back creditworthiness of the network, and to provide access to energy resources and rights of way. Government also sets taxes, and, in many cases, prices, of competing fossil fuels, as well as renewable incentives and overall energy policy. So, clearly the “agency level” for District Heating is the “Community” which must create the district, obtain and guarantee financing, and get local stakeholders on board that DH is the right path. The supportive policies of Sweden, Denmark, and other Scandinavian countries for DH from the 1970s until today have been a decisive factor in making those countries DH leaders.
- **High energy density heating load.** Because of the cost of distribution piping, District Heating is most economical where it can sell the most energy for a given capital investment. Thus the DH focus on dense urban centers in cold climates. The minimum energy density at which a DH system can be commercially viable has been characterized in terms of load per unit distribution piping length, with a rule-of-thumb threshold being a linear heat density of 2.5 MWh/m (e.g., Büchele et al, 2016). It is increasingly common to characterize DH load suitability, using geographical information system (GIS) mapping, in terms of area-based energy density. Using this approach, Connolly found that a thermal density of about 4 GWh/km² (15 TJ/km²) corresponded pretty well with actual Danish DH networks (Connolly, 2014). This is probably a reasonable figure for District Heating *theoretical potential*, but defining the heat density threshold

for a real DH system must take into account the country-specific market incentives. Thus, a heat density threshold of around 6 to 14 GWh/km² (20 to 50 MJ/m²) makes sense for countries such as Sweden and Denmark with strong DH mandates, but, to be economical, DH systems face much higher energy density thresholds in countries, such as Germany or the US, with fewer incentives and mandates (Werner, personal communication, 2019).

- **Integrated and sustainable energy strategy.** Energy strategy is increasingly critical for District Heating success. Early 1st and 2nd Generation DH systems were essentially community-scale fossil-fueled boilers that operated autonomously. But modern 3rd and proposed 4th Generation DH systems are, by their nature, integrally networked into the larger energy grid. Using biomass and industrial “waste heat”, for example, requires coordination, mandates, and incentives to energy providers to ensure energy availability. For CHP to be an economical source of district heat requires at least a regional-scale decision to use co-generators as an integral part of the *electrical* grid. And there are opportunities for grid-level savings, for example, by not upgrading natural gas distribution networks where district heat is available. For 4th Generation DH to succeed, the need and promise of integration is even greater. 4th Generation DH will coordinate in real time with smart grids on the supply side and smart buildings for demand. And to reduce CO₂ emissions, 4th Generation DH systems will need to access large-scale renewable resources, such as bioenergy, solar thermal, and geothermal plants, as well as community-scale “ambient energy” resources, including sewage waste streams, rivers, lakes, and oceans, that can be upgraded using central heat pumps.

1.2 ADOPTION PATH

1.2.1 Current Adoption

Current District Heating Adoption and Carbon Intensity

Today’s District Heating reality is far from realizing the future potential of District Heating to deliver economical space heating and reduced GHG emissions. In 2014, as Table 1.2 illustrates, approximately 80,000 DH systems worldwide sold roughly 1,400 TWh of heat for building space heating. Worldwide, this represented about 11% of all installed heating equipment, and 16% of the overall space heating delivered energy of 9,100 TWh (13% of building space heating final energy) (Werner, 2017; IEA ETP 2017; Drawdown calculation).

Table 1.2 District Heating adoption and carbon intensity in selected regions and countries

Region / Country	District Heating Building Final Energy* (TWh)	District Heating Share of Space Heating TAM (%)	Carbon Intensity (g CO ₂ / MJ heat delivered)
World	1,449	13	52
European Union	356	12	31
China	322	19 (80% of N. China)	85
Russia	811	72	46
USA	17	1	N/A
Sweden	N/A	52**	3
Denmark	N/A	63**	N/A

*Building Space Heating Final Energy for World; Space Heating + Water Heating Final Energy for Regions; (Source: IEA ETP, 2017; Werner, 2017) (**Source: IEA ETP, 2016)

Russia, China, and the European Union account for 85% of district heat deliveries. Countries and regions with adoption rates above 50% include Northern China, Russia, Iceland, Denmark, Sweden, Finland, and Poland. US DH deliveries are under-reported by IEA because many US DH systems are owner-operated university campuses, military bases, hospitals and industrial sites (Werner, 2017; IEA ETP 2017). The DH share of US space heating TAM, including private systems, is likely ~5% (EIA, 2018).

Carbon intensity varies greatly among these systems, as Table 1.2 illustrates. Worldwide in 2014, 56% of DH heat supplied was “recycled” and only 9% renewable (Werner, 2017). In fact, in 2014, fossil fuels (natural gas, coal, and oil) comprised 90% of DH primary energy worldwide and 70% in the European Union. (Werner, 2017) So the potential of District Heating to reduce greenhouse gas emissions is far from realized today, especially outside the EU. China’s very large DH footprint, fueled 90% by coal boilers and CHP plants, has very high CO₂ emissions and severe pollution. Russia, which fires its DH systems predominately with natural gas, has much lower relative CO₂ emissions (Werner, 2017; Gong & Werner, 2014, p.30).

Factors Contributing to District Heating Adoption and CO₂ Emissions Reduction

In order to quantify the factors that have contributed to District Heating adoption – and could contribute to the growth of GHG emission-reducing DH systems in the future – it is valuable to examine some contrasting district heating cases, the factors that have driven them, and the outcomes they have achieved.

China District Heating

Under the Huai River Policy mandate, District Heating in China is limited to the 70% of the mainland north of the Huai River, where DH supplies 80% of building space heating. District Heating is being

prohibited south of the Huai. With this mandate, DH in China has grown 15% annually from 277 million m² of building area in 1991 to 4,357 million m² in 2010.

Key factors that have shaped China's DH evolution, and which will drive future improvements, include: (Xiong, 2015; Xilang, 2015; Gong & Werner, 2014)

- **Shortage of natural gas and resultant pollution.** 48% of Chinese DH is sourced from coal-fired boilers; 42% from coal-fired CHP. As a result, District Heating has emerged as the main source of PM 2.5 pollution in Northern China.
- **Grid integration and utilization of CHP and industrial waste heat.** Since China's DH boilers operate at low efficiency, DH heat supply could be shifted economically to CHP and industrial waste heat sources, reducing overall pollution. In fact, if China were able to achieve the same heat recovery efficiency as Sweden, such grid infrastructure integration would deliver 732 TWh of heat with DH by 2030 and reduce primary energy consumption by 50%. A related grid opportunity is reducing wind energy curtailment (when turbines are feathered, usually due to inadequate load), now 25%, which could be eliminated by flexible CHP dispatch and heat storage to better balance energy supply / demand.
- **DH distribution network improvements.** Leaks and thermal losses total ~30% of total heat supply.
- **Policy and metering reform.** Currently DH is sold to buildings on a per area basis. Building insulation and temperature control are poor, leading to an estimated 20% waste that could be eliminated by energy-based billing, stricter building energy efficiency standards, and smart controls.
- **Ambient energy heat sources.** Heat pumps and lower-temperature heat delivery represent key potential technical improvement opportunities that would open the door to using low-temperature ambient heat resources, such as sewage waste streams and surface water.

In summary, driven by government mandate and lack of natural gas, District Heating has been implemented in Northern China on a vast scale. In the past, energy efficiency and GHG emissions were minor considerations. The resulting DH systems are inefficient and highly-polluting. The Chinese government now has identified DH energy consumption and emissions as key priorities and has developed a plan to accelerate refurbishment of its DH network (IEA, 2016). These technical and policy improvements will require decades to implement.

Sweden and Scandinavian District Heating

Sweden offers a remarkable example of how successful District Heating can be, both economically and environmentally. Table 1.3 summarizes key data reflecting the Swedish District Heating evolution.

Table 1.3 District Heating in Sweden

Issue	1984	2014
Market:		
Market share of building space heating (%)	33%	55%
Share: Multi-family residential (%)	N/A	89%
Share: Single-family residential (%)	N/A	17%
Share: Service sector buildings (%)	N/A	80%
Average building specific demand (kWh/m ²)	200	130
Heat sources:*		
Recycled heat** (%)	30%	73%
Renewable boilers (%)	5%	22%
Fossil-fueled boilers and electricity (%)	65%	5%
Primary Energy Sources:*		
Renewables, heat recycling & biomass*** (%)	20%	87%
Fossil fuel (%)	70%	13%
CO ₂ Emissions (g/MJ)	62	9

Source: Sven Werner, *District heating and cooling in Sweden, 2017*

*2015 data

**Recycled heat: Industrial excess heat, flue gas condensation, ambient heat input to heat pumps, and combustion of municipal and industrial waste.

***Biomass: Forest, agricultural and imported waste

As Table 1.3 illustrates, District Heating in Sweden has grown from 33% of building space heating in 1984 (and less than 5% in 1960) to 55% in 2014, including 89% of multi-family residential buildings and 80% of commercial buildings. Swedish DH heat sources have also evolved dramatically: In 1984 fossil-fueled boilers and electricity provided 65% of district heat, while recycled heat, CHP, and renewables provided 35%. By 2015 the situation was reversed with recycled heat and renewables providing 95% and fossil fuels / electricity only 5% of district heat. Correspondingly, primary energy shifted from 20% renewable / recycling / biomass in 1984 to 87% in 2015, and CO₂ emissions dropped from 62 g/MJ to 9 g/MJ. With Sweden's huge forest industry and resources, biomass has played an outsized role, delivering 46% of 2015 primary energy.

How did Sweden achieve these outcomes? There are several key success factors:

- **Government strategy and policy.** Faced with the 1970s oil shocks, Sweden committed to using local fuels and heat resources that otherwise might be wasted, in order to ensure energy security and cut expensive oil imports. Sweden also committed to reducing GHG emissions in the 1980s and imposed a carbon tax of ~\$30/ton CO₂ in 1991, which rose to ~\$130 in 2016. Perhaps surprisingly, Sweden has never imposed a mandate for buildings to use DH networks. Instead it has used the CO₂ tax to reduce fossil fuel use, and incentives for energy efficiency as well as DH hookups for new homes, under the “million homes program”, as early as 1965. One side benefit of the CO₂ tax is that 25% of building space heating, especially in areas not dense enough for DH, is delivered by electric heat pumps.
- **Integrated energy strategy.** With 32% of 2015 DH heat supply from recycled heat and 22% from CHP, integration of District Heating networks with the electric grid, with industry, and with municipal and industrial waste processing is essential. This is especially noteworthy in that energy markets in Sweden are competitive and energy suppliers are free to select customers. But the CO₂ tax and energy conservation requirements punish fossil fuel use, making the business case for non-fossil space heating, and fostering cooperation across energy sectors.
- **Innovation.** Sweden never implemented 1st Generation District Heating systems. Early systems were 2nd Generation and faced with the 1970s oil shocks, Sweden, along with Finland and Denmark, led the charge to develop the more-efficient, lower-cost 3rd Generation District Heating systems.

The Swedish model for District Heating is not without faults. Throughout its history, there have been competitive battles between municipal and commercial DH providers, between DH providers and other space heating solutions, as well as across industrial sectors. But, at the end of the day, the Swedish District Heating model has proven to be a resilient, efficient, economical, energy secure, and low GHG space heating solution.

And Sweden faces challenges going forward: 4th Generation DH networks will operate at lower temperatures and have lower heat demand, as building envelopes continue to improve. This will require even greater integration with “smart” grids and buildings, as ambient sources boosted by heat pumps play a greater role. The role of biomass in Swedish DH, especially, is likely to transform as competition for biomass, both as a fuel and as an industrial feedstock, increases (Ericsson and Werner, 2016). The result will likely be less use of biomass for District Heating, with remaining use more efficient, e.g., biomass-fired CHP instead of biomass boilers, as well as increased input of ambient energy boosted by central heat pumps (Averfalk, Large heat pumps in Swedish district heating systems, 2017).

District Heating in other Scandinavian countries, especially Denmark, provides additional perspective. Denmark, with far less biomass than Sweden, has achieved 63% DH penetration using a network of 3rd Generation DH systems (80C supply, 40C return temperatures). Denmark has reduced CO₂ emissions by imposing stringent building energy efficiency standards and a roughly \$0.04/kWh fossil fuel tax. These have spurred intensive use of fossil-driven CHP (as opposed to boilers or stand-alone electric generators). For the future, Denmark is working to develop ambient / heat pump, solar thermal, and geothermal energy sources (Nordic ETP, 2016; Furbo, 2015).

1.2.2 Trends to Accelerate Adoption

Factors and Trends to Acceleration District Heating Adoption

Here is a good starting point for identifying the factors and trends that can accelerate District Heating adoption worldwide:

- Key factors and actions that have led to DH success in the past, recognizing the importance of social and political context.
- Scenario drivers that lead analytically to accelerated DH adoption.

Key success factors to accelerate District Heating adoption include:

1. **Integrated government strategy and policy:** The success of Sweden and other Scandinavian countries in successfully growing District Heating, as well as China's positive and negative results, point the way towards the right kind of government intervention. It is notable that Sweden does not have a mandate for buildings to use DH. Instead, Sweden's DH-related policies have targeted long-term national objectives:
 - Cut GHG emissions.
 - Cut costs.
 - Reduce building energy consumption.
 - Foster energy independence.

Sweden executed its strategy through a combination of “carrots and sticks” – a carbon tax, building energy efficiency standards, as well as incentives and loans to implement these standards. The result has been a long but steady march over 40+ years to District Heating success.

2. **Integrated and sustainable energy strategy:** As noted above, modern 3rd and proposed 4th Generation DH systems, by their nature, need to be integrally networked into the larger energy and industrial grid. Whether the energy source is CHP, industrial or municipal waste, or ambient energy upgraded by large heat pumps, integration and coordination are key. Beyond making

everything work day-to-day, energy integration and energy strategy are critical to minimize costs. These include capital costs, for example avoiding installation of natural gas distribution piping or furnaces that will not be needed. It also means operational costs, for example, coordinating in real time the electrical output of CHP plants with the rest of the electric grid, and ensuring that renewable resources, such as solar or wind – which have zero fuel cost and zero GHG emissions – are dispatched *first* in the loading order and not curtailed.

3. **High energy density heating load and a strong competitive market:** As discussed above, District Heating is most competitive where there is high heat density, primarily urban areas and campuses. But the market challenge of the future will be much more nuanced and dynamic. Going forward as the world advances toward 4th Generation, economical DH networks will need to serve smaller heating loads – by design – and do so with lower-quality energy inputs against increasingly intense competition from individual building systems, such as high-efficiency heat pumps and solar. In such a competitive future environment, government policy needs to foster competition, not monopoly: The Scandinavian experience clearly shows that a vibrant, competitive market of products and ideas can lead to continually-improving, economical, energy-efficient, and low-impact DH systems. China, by contrast, has established one of the largest DH networks in the world, but one can speculate that if alternative DH designs, or other heating alternatives, had been able to compete over the years, the Chinese DH network might not be the polluting “white elephant” that it is today.
4. **Technological innovation:** Past experience demonstrates strongly the importance of innovation in District Heating. 3rd Generation DH originated in Scandinavia to address the “oil crisis”. Likewise, going forward, DH has much to offer, but competitors are advancing too: Renewable energy costs are dropping fast. Heat pump efficiencies are rising, and heat pumps have the advantage of being modular and able to provide both space heating and cooling. Innovation will be essential.

1.2.3 Barriers to Adoption

Key barriers to adoption of District Heating include:

- Lack of requisite government strategy and policy “carrots and sticks” (discussed above) that foster District Heating. Social and cultural factors look to be major drivers of such strategy and policy. There is a strong correlation between high DH penetration and countries with influential central governments: District heating penetration is highest in China, Russia, former Soviet Union, Eastern Europe, and Scandinavia. DH is weaker in other Western European countries and in the US, which has no national energy strategy as such (see listings IEA ETP, 2016, p. 119).

- Low competing fossil fuel prices and fossil fuel subsidies, explicit and implicit.
- Competition from advancing individual-building space heating systems. This is one of the main factors muting District Heating's adoption in IEA's scenarios (Dulac, personal communication, 2019).
- Lack of integrated and sustainable energy strategy and implementation. The US, for example, by design, manages its electric grid regionally, not nationally, making integration a challenge. Many developing countries are stretched just working to meet electric demand growth.
- Lack of high energy density locations. This is a barrier in less densely populated locations today. And going forward, shrinking building space heating loads will make District Heating less economic, though increasing growth of urban areas will be a plus.

Heat Roadmap Europe has explored a range of barriers, especially those affecting European DH, and how to address them (Trier, 2018).

Implementation Issues

District Heating, by its nature as a centralized community-wide energy system, faces implementation issues unlike those of any single-building space heating system, such as a furnace, boiler, or heat pump. The distribution network, the central unique feature of a DH system, represents a large up-front capital expense and ongoing operational cost. Distribution requires electrical pumping energy, and can be a source of significant thermal losses, in addition to thermal energy actually sold to building customers. Because of the large capital commitment, the network also represents a significant risk of obsolescence as new district-based or individual-building heating technologies come along, and as building energy efficiency standards increase (reducing heat sales).

Each District Heating system faces its own set of implementation issues, driven by local and national objectives and challenges. Some of these issues will be explored along with how they have been addressed – or not – in the context of specific cases in “Current Adoption” below. But one can identify several crosscutting issues that every District Heating system must address to be cost-competitive and environmentally sustainable:

- Obtaining construction financing before energy revenues are received, and assuring adequate ongoing operating revenue.
- Obtaining a dense space heating load and defending it against competitors.
- Obtaining or accessing assured, reliable renewable energy supplies.
- Accessing public utility rights-of-way.

1.2.4 Adoption Potential

Overall District Heating Adoption Potential

The literature contains considerable work exploring the long-term adoption potential of District Heating. In the past such research has been based on rules of thumb, e.g., regions with energy density above 15GWh/km². But increasingly such studies use GIS mapping tools to identify in small detail areas suitable for District Heating. Table 1.4 summarizes recent important studies:

Table 1.4 District Heating adoption potential in the literature

Scope of Forecast	Adoption (% Residential & Commercial Heat Demand)	Date for Forecast	Source	Notes
European Union	50%	2050	Connolly, 2014	Response to EC forecast; obtained 15% lower cost with 50% DH penetration
14 EU countries	44%	2050	Paardekooper, 2018	Heat Roadmap Europe
Germany, France, Belgium, Netherlands, UK	50%	2030	Gils, 2012	GIS mapping
USA	47%	2030	Gils, 2013	GIS mapping; 5 GWh/km ² minimum demand density
USA	13%	2030	Gils, 2013	GIS mapping; 20 GWh/km ² minimum demand density
Austria	67%	2025	Büchle et al, 2016	Adoption depends sensitively on DH connection rate
European Union	50%	2050	David, 2017	Up to 30% of DH provided by large heat pumps upgrading ambient sources, including sewage water, ambient water, industrial waste heat, geothermal heat
China	N/A	2030	Xiong, 2015	Forecasts 60% less energy consumption, 15% lower cost

As Table 1.4 illustrates, DH adoption potential is viewed as high, perhaps 50%+, especially in densely populated European countries. US potential is substantial in total energy but (depending on the minimum energy density assumption) lower as a share of total building heating demand. It is important to note the role of GIS mapping in accurately assessing potential DH targets down to hectare scale (Werner, personal communication, 2019), and the increasing role of large heat pumps in upgrading ambient heat sources that

are uniquely community oriented, for example, sewage water, surface water, and low-grade industrial waste heat (David, 2017).

Renewable District Heating Adoption Potential

But what share of future District Heating adoption will be renewable energy that can replace fossil fuels and reduce GHG emissions? IEA forecasts a ~50% increase in District Heating by 2060 in its B2DS scenario as a result of “incentives for excess heat recovery and energy balancing with variable renewable energy that encourage the development of energy-efficient, renewable and integrated district energy solutions” (IEA DHC, 2017, p. 145). So clearly, these future DH systems will be primarily renewably fueled. A recent Heat Roadmap Europe (HRE) article forecast that European DH networks could be up to 100% decarbonized, including ~30% CHP excess heat, ~25% large heat pumps using renewable energy, 25% industrial excess heat, and other 5% renewables, including geothermal and solar thermal (Paardekooper, 2018). And an earlier article modeled a EU27 future with 50% District Heating penetration, of which only 26% was fossil fuel power generation excess heat and heat from boilers. The remaining 74% of the DH energy was supplied by renewably-based sources, including large-scale heat pumps, biomass, waste-to-energy incineration, industrial excess heat, geothermal and solar thermal.

IEA Future Adoption Scenarios.

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

- ***The Reference Technology Scenario (RTS)** takes into account today’s commitments by countries to limit emissions and improve energy efficiency, but would still see a 2.7°C rise by 2100.*
- ***The 2°C Scenario (2DS)** – aims for a 50% chance of limiting the average global temperature increase to 2°C by 2100.*
- ***The Beyond 2°C Scenario (B2DS)** includes technologies and adoption that are pushed to their maximum practicable limits across the energy system in order to achieve net-zero emissions by 2060, and it is consistent with a 50% chance of limiting average future temperature increases to 1.75°C.*

What do the IEA ETP scenarios forecast for District Heating adoption and growth?

Overall space heating forecast. Overall, IEA forecasts that space heating final energy consumption will fall in both relative and actual terms over the next 40+ years. Relative to overall building energy consumption, IEA projects that space heating will drop from 32% of 2014 building final energy to 20% by 2060 in its RTS scenario. This drop is partly due to building envelope improvements and partly a

result of growth of higher-efficiency heat pumps and other equipment. In the 2DS case, 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.

District Heating forecast. IEA's scenarios project that District Heating, along with renewables and heat pumps, will significantly increase their share of building space heating by 2060. While this increase is moderate in 2DS, due to lack of incentives to shift away from natural gas, it increases by 50% in B2DS, due to incentives that encourage energy efficient, renewable energy solutions. Specifically, as Table 1.5 and Table 1.6 illustrate, IEA projects that:

- DH installed equipment serving building space heating and water heating will increase from 11% of 2014 installed equipment to as much as 17% in 2060 under B2DS.
- Although the total amount of space heating final energy that DH will provide in the future is fairly flat across IEA's three scenarios, the *share* of space heating demand provided by District Heating will increase by 2060, from 13% of final energy in 2014 to as much as 26% in 2060 under B2DS.

Table 1.5 Space and Water Heating - DH adoption and impact in 2014 and 2060 in IEA ETP scenarios

Building Space Heating & Water Heating	RTS 2014	RTS 2060	2DS 2060	B2DS 2060
Total Scenario Final Energy Consumption (% RTS 2060)	N/A	100%	78%	62%
Total Scenario Space + Water Heating Emissions (% RTS 2060)	N/A	100%	53%	18%
District Heating Adoption of Installed Equipment (%)	11%	8%	16%	17%

Table 1.6 Space Heating - DH adoption and impact in 2014 and 2060 in IEA ETP scenarios

Building Space Heating	RTS 2014	RTS 2060	2DS 2060	B2DS 2060
Total Scenario Final Energy Consumption (% RTS 2060)	N/A	100%	69%	55%
District Heating Adoption of Final Energy (% RTS 2060)	N/A	100%	80%	95%
District Heating Share of Final Energy Consumption (% of TAM)	13%	15%	17%	26%

Total Scenario Space Heating Emissions (% RTS 2060)	N/A	100%	49%	18%
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Important conclusions:

1. District Heating, along with high-efficiency heat pumps and building envelope improvements, plays a major role in reducing building heating final energy consumption in the 2DS and B2DS scenarios.
2. Renewables, integrated District Heating systems, and high-efficiency heat pumps play a significant role in 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 CO₂ emissions of B2DS (where building fossil fuel is eliminated) in 2060.
3. “Greening” the grid plays an important role in reducing CO₂ 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.

1.3 ADVANTAGES AND DISADVANTAGES OF DISTRICT HEATING

1.3.1 Similar Solutions

To win, District Heating must compete with a raft of entrenched and steadily-improving individual-building space heating systems, including:

- High-efficiency air-source heat pumps
- Ground-source and water-source heat pumps
- Fossil fuel combustion furnaces and boilers for space heating
- Electric resistance heating
- Solar heating and cooling systems

Among these, fossil-fueled furnaces and boilers and electric resistance heating are ubiquitous – but great energy wasters and sources of CO₂ emissions. Solar heating is renewable but still a small niche.

Heat pumps have a unique position vis-à-vis District Heating. As the Swedish experience illustrates, heat pumps represent both a partner and a competitor for DH systems: Heat pumps compete with DH in many cities. Outside the urban areas in which DH leads, individual building heat pumps serve a large share of the heating load. But some of the most advanced high-efficiency DH systems *employ* large centralized heat pumps to scavenge ambient heat and waste heat, and for “temperature boosting” (e.g., see Stanford Energy Systems Innovation webpage). And as distribution temperatures fall, as envisioned for 4th Generation DH, District Heating systems will require more temperature boosting heat pumps *on the customer side*, e.g., to provide hot water or to serve buildings with antiquated heat distribution.

Deciding between District Heating and heat pumps, or other in-building heating systems, ultimately boils down to a detailed assessment of energy consumption, GHG emissions, and cost compared with energy objectives and strategy. A comparison of technologies is shown in Table 1.7.

1.3.2 Arguments for Adoption

Fossil fuel combustion for space heating is one of the greatest wastes of high-quality natural resources and one of the largest sources of GHG emissions in the world. District Heating, in suitable locations and properly developed, can easily and economically deliver the low-quality energy needed, typically warm air or water at 50C to 80C. DH can have lower life cycle costs than other technologies.

By utilizing local energy resources that would otherwise be wasted, District Heating systems represent a unique “economy of scope” solution for replacing fossil fuel-fired furnaces and boilers with available renewables and waste energy (Werner, 2017; Connolly, 2014). In this way, District Heating offers unique

potential as an economical space heating solution for reducing primary energy consumption and GHG emissions.

1.3.3 Additional Benefits and Burdens

Additional benefits resulting from extensive implementation of District Heating include:

- Reduced investment in fossil fuel-related infrastructure, especially in-building systems – furnaces and boilers (which are replaced by much simpler heat exchangers), and associated exhaust systems, plumbing, and piping – as well as natural gas transport and distribution networks.
- District Heating implementation, if renewable sources are used, represents a health benefit by reducing respiratory disease and fire risk, especially for buildings now heated by coal or wood.

Additional burdens include:

- Need for favorable government policy and legal / regulatory support, as well as fair treatment vis-à-vis competing options.
- Requirement of coordination with the electric grid, industries providing waste heat, and other partners.
- Need for a large capital investment and construction project to install the network – before revenue is received.
- Installing an underground system in an urban setting with pre-existing infrastructure can be technically challenging and costly.
- Need for sophisticated design expertise which may not be available in some locations.
- Necessity for a substantial, reasonably-predictable heating load, ideally year-round.
- Requirement for securing and connecting heating customers.

Key risks and weaknesses of District Heating include:

- Risk of obsolescence of heat sources and the distribution network (as has happened in China and in older US DH systems) due to investment “lock-in” of CAPEX.
- Risk of future major changes to technology or government policy.

Table 1.7 District Heating Technology Comparison

Technology	Service (Heating / Cooling)	Breadth of Application	GHG Emissions Reduction	Fossil Energy Reduction	First Cost	Life Cycle Cost	Comfort and Health	Resilience
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	Heating	Low to Medium	Medium to High	Medium to High	High	Low to Medium	High	High
High-efficiency heat pump	Heating / Cooling	High	High	High	Medium to High	Low	High	Medium

Table 1.8 Ratings key

Rating	Service (Heating / Cooling)	Breadth of Application	GHG Emissions Reduction	Fossil Energy Reduction	First Cost	Life Cycle Cost	Comfort	Resilience
High	N/A	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	N/A	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	N/A	0% to 33% of buildings	0% to 33%	0% to 33%	Bottom 1/3	Bottom 1/3	Bottom 1/3	Large risk of disruption

Table 1.7 compares District Heating with four space heating and cooling alternatives (with the Ratings Key shown in Table 1.8). The table examines each option in terms of breadth of application, GHG emissions, fossil energy reduction, cost, comfort and health, and resilience.

Compared with the options that are common in developed countries (gas furnace and low-efficiency heat pump), District Heating provides equivalent heating service and comfort, but less breadth of application than these modular heating solutions, due to DH's need for high energy density locations. But District Heating offers far higher potential for reducing GHG emissions and fossil energy consumption. Economically, DH requires a higher first cost, but offers lower life-cycle cost.

Compared with "Coal or wood combustion", District Heating offers much higher comfort, safety, and health.

“High-efficiency heat pumps”, 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 suitable, can be a low cost and highly-resilient option.

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) is what constituted the results.

Table 2.1 summarizes key analytical aspects of the District Heating modeling approach. The overall modeling scope is building space heating where District Heating is competitive. Water heating is not modeled, although it is a natural adjunct and commonly provided by many DH systems.

Table 2.1 District Heating modeling approach

Attribute	Specific Values and Quantification
Modeling Scope	Space heating for residential and commercial buildings where District Heating is competitive (described in Section 2.4) in replacement of in-building equipment, including: Combustion equipment including gas- and oil-fired boilers, furnaces and unit heaters; wood and coal stoves Electric resistance furnaces and unit heaters Low-efficiency residential and commercial air-source heat pumps, both central and room units
Solution	Renewable energy-based District Heating for building space heating
Agency	The Community
Functional Unit	Space Heating annual “Delivered Energy” (TWh) for District Heating and conventional heating equipment
Implementation Unit	Space heating Delivered Energy capacity (power; TW) as the Implementation Unit for District Heating and conventional heating equipment

This Solution is *Renewable District Heating* for building space heating. As detailed in the Literature Review, District Heating, where it can be economically delivered, offers unique potential for reducing GHG emissions by replacing individual fossil-fueled heating equipment with available local heat resources – especially renewable and “ambient” energy resources that may not be accessible to individual buildings.

The “agency” for District Heating is “Community”, consistent with DH’s unique role as a community energy system. And in a departure from previous analyses, space heating *delivered thermal energy* is the *Functional Unit* of measure, consistent with other Project Drawdown building technology solution updates. Delivered energy corresponds with the functional purpose of District Heating – providing space heating comfort. Total energy use is aggregated under terawatt hours thermal (TWh (th)).

Operationally, the modeling effort is geared to use the latest published data and forecasts available. These include:

- Updated data and scenario forecasts of building energy use, especially space heating delivered energy requirements
- Updated heating equipment installed stock data and equipment stock scenario forecasts
- Forecasts of space heating equipment efficiencies, energy consumption, and GHG emissions
- Scenario of District Heating renewable energy content and market adoption
- Pending District Heating technological advances, such as “4th Generation” District heating, and new thinking which impact both the design and potential of District Heating.

2.2 DATA SOURCES

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

Table 2.2 Key Data Sources Used

Input Data	Key Data Sources
Future Projections of Space Heating Delivered Energy Total Addressable Market	IEA ETP (2017) Greenpeace Energy Revolution (2015)
Heating Equipment Efficiencies, Costs and Lifetimes	US EIA (2018) LBNL (2015) JRC (2013)
District Heating Adoption, Future Renewable Energy Content, and CO₂ Trajectory	IEA ETP (2017); IEA WEB (2018); Dulac, IEA (2019) Greenpeace Energy Revolution (2015) Werner (2017) Heat Roadmap Europe (2018) Paardekooper (2018, 2019)
District Heating in China	Xiliang (2015) Xiong (2014, 2015)
District Heating in Russia	Makarova (2015)

Primary sources for global building space heating delivered energy projections include IEA ETP (2017) and Greenpeace Energy Revolution (2015). Drawdown's calculation of space heating Delivered Energy Total Addressable Market, based on these sources, is presented in Section 2.3.

Sources for heating equipment efficiencies, costs, and lifetimes (including District Heating Equipment) include the US Energy Information Agency (EIA), LBNL, and EU's JRC. First costs and operating costs of conventional equipment were calculated based on weighted averages of published cost data.

Key sources for the critical question of the renewable content / CO₂ emissions of future District Heating systems include IEA ETP (2017), IEA World Energy Balances (2018), Dulac, IEA (2019), Heat Roadmap Europe (2018), and Paardekooper (2019). The Drawdown calculation of future CO₂ intensity projections based on these sources is described in Section 2.4.

Xiliang (2015) and Xiong (2014, 2015), in addition to IEA ETP (2017), are prime sources for data and projections of District Heating in China. Makarova (2015) is the prime source for information on District Heating in Russia.

2.3 SPACE HEATING DELIVERED ENERGY TOTAL ADDRESSABLE MARKET (TAM)

With delivered energy as the functional unit, the 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 (IEA ETP, 2017) and space heating equipment efficiency, using historical data and future projections for both quantities (EIA, 2018; IEA ETP, 2017).

Table 2.3 shows 2014 global residential and commercial building space heating delivered energy TAM: (Drawdown calculation)

Table 2.3 2014 Space Heating Delivered Energy TAM (Drawdown Calculation based on IEA ETP, 2017)

Energy Source	2014 Space Heating <u>Delivered</u> Energy	
	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%
District Heating	1,449	15.9%
Total	9,131	100%

2014 delivered energy TAM is about 17% *below* final energy use. This is due to efficiencies below 100% for combustion-based space heating equipment which provides the majority of space heating delivered energy, compensated somewhat by electric heat pump efficiencies above 100% (the share of space heating delivered energy provided by electrical equipment, 13.3% of the TAM, is ~87% resistance heating and 13% heat pumps). District Heating represents about 13% of space heating final energy and 16% of delivered energy. Since District Heating is delivered to buildings as heat, there are no in-building combustion losses, the efficiency of DH is 100%, and DH final energy equals DH delivered energy. (This might change in future low-temperature DH systems using in-building “booster” heat pumps to increase distribution temperature.) Renewable District Heating represents about 10% of all 2014 DH, i.e., about 1.6% of all delivered energy (IEA ETP, 2017; Dulac, IEA, personal communication, 2019).

To estimate future delivered energy TAM, four TAM scenarios were developed, “reference”, “conservative”, “ambitious”, and “maximum”. Table 2.4 matches these four Drawdown delivered energy TAM scenarios with the corresponding IEA ETP 2017 and IEA ETP 2016 scenarios:

Table 2.4 Drawdown Delivered Energy TAM Compared with IEA ETP Scenarios

Scenario	Baseline	Conservative	Ambitious	Maximum
Drawdown Space Heating Delivered Energy TAM Scenario	Reference Case	Conservative Case	Ambitious Case	Maximum Case
IEA ETP 2016	6DS Space Heating & Cooling	4DS Space Heating & Cooling	2DS Space Heating & Cooling	
IEA ETP 2017		RTS Space Heating & Cooling	2DS Space Heating & Cooling	B2DS Space Heating & Cooling
2014 TAM (TWh)	9,131	9,131	9,131	9,131
2060 TAM (TWh)	9,131	8,670	6,366	6,586

The 2014 to 2060 TAM estimates 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 gradually reduce space heating delivered energy.

This calculation also considers switching between product classes, which is especially relevant for District Heating where, due to the increased first cost of condensing furnaces and the potential for substantially lower fossil fuel use for DH, there is projected to be substantial switching from fossil-fuel based furnaces to District Heating in densely-populated locations as a prime GHG reduction strategy.

2.4 RENEWABLE DISTRICT HEATING (RDH) ADOPTION SCENARIOS

Paralleling the TAM approach, the Renewable District Heating (RDH) adoption analysis examines two different types of adoption scenarios, a baseline Reference Case (REF) and a set of Project Drawdown Scenarios (PDS) with varying levels of RDH. Published results compare each PDS to the REF, and thus focus on the *change* to the world relative to the REF baseline. These adoption scenarios are based on the approach defined below.

2.4.1 Adoption Scenario Modeling

Adoption scenario modeling for Renewable District Heating needs to answer two key questions:

1. What share of the space heating TAM is projected to be District Heating adoption?
2. What share of DH adoption will be *Renewable* District Heating and where will this come from?

District Heating Adoption.

As noted in the individual scenario descriptions, the Drawdown adoption scenarios are formulated so that overall District Heating adoption is consistent with the corresponding IEA ETP 2017 building final scenario. So, the Drawdown adoption scenario shares of space heating TAM are consistent with that body of work.

Renewable DH Adoption.

Drawdown's District Heating modeling projects renewable energy content of the District Heating system via DH CO₂ intensity (g CO₂/kWh) trajectories:

1. Renewable DH fraction (t, scenario) = 1 – DH CO₂ intensity (t, scenario) / DH non-renewable CO₂ intensity (2014, all scenarios).
2. DH non-renewable CO₂ intensity (2014, all scenarios) = 333 g/kWh

So, for example, 2014 RDH fraction = 1- 300 g/kWh / 333 g/kWh = 10%.

Calculating Initial CO₂ Intensity.

The CO₂ trajectories, in turn, are based on inputs from IEA (IEA ETP, 2017; John Dulac, IEA, Personal Communication, 2019), other sources delineated below, and Drawdown calculations: The initial worldwide DH CO₂ intensity of 300 g/kWh, is a bit lower than the 310 g/kWh recommended by IEA, but higher than other literature values, for example, Werner's value of ~198 g/kWh (Werner, International review of district heating and cooling, 2017).

This Drawdown value is consistent with the sources of DH for space heating: (IEA WEB, 2018, p.II.5)

1. About 70% Combined Heat and Power (CHP) plants that burn fuel, mostly coal, followed by natural gas; with some biomass and waste.
2. About 30% Heat Plants that burn fuel, mostly natural gas, followed by coal, some biomass and waste, oil, and very small amounts of solar / geothermal.

The Heat Plant portion yields CO₂ intensity of about 333 g/kWh “at the plant” (IEA WEB, 2018; Drawdown calculation) plus transmission / distribution losses. But estimating the CHP portion has a core ambiguity: What portion of the fuel consumed should be attributed to the District Heating output vs. to the electrical output? CHP heat output is not “free”: CHP plants have significantly lower electricity generation efficiency than stand-alone Electricity Plants (for gas, 35% vs. 45%; for coal, 32% vs. 38% (IEA, *ibid*)). As an “allocation problem”, there is no definitive answer. Werner has addressed this

ambiguity using a “virtual heat pump” approach (Lowe, 2011) with a COP of 10, resulting in his 198 g/kWh specific CO₂ emissions result (Werner, *ibid*, p. 625).

But, given the size of the electricity generation reduction in comparing a CHP plant with an Electricity Plant (IEA WEB, 2018), an effective COP of 2.9 (fraction of CHP energy representing useful heat “gained” of 23.4% / fraction of CHP energy that is electricity “lost” 8%) seems more appropriate. This yields a plant output value of 212 g/kWh for the CHP portion, but this needs to be increased to incorporate all of the “transformation losses” and transmission / distribution losses contained in the IEA energy balance computation (IEA WEB, 2018). These losses represent waste and increase the CO₂ intensity of heat and electricity outputs. So, overall, 300 g/kWh seems a reasonable estimate of current DH CO₂ intensity.

Calculating Future CO₂ Intensity Trajectories.

The future CO₂ trajectories used in the Drawdown Renewable District Heating modeling, stated in Table 2.5, are less aggressive than IEA’s recommendation – 2DS dropping to zero in 2050 and negative thereafter; B2DS even more aggressive. The reason is that IEA projects negative CO₂ emissions that result from bioenergy combustion paired with carbon capture and storage (CCS) (Dulac, IEA, 2019). Large-scale CCS is outside the Drawdown approach of modeling only commercially available technologies.

Can DH CO₂ Intensity Reach Zero By 2050 To 2060?

This is technically feasible if sufficient renewable resources are brought to bear. But how practical is it? Especially, what past examples of Renewable District Heating and projections of future adoption support the prospect of 100% Renewable DH worldwide?

For Europe, high adoption of renewable district heating is well supported by past experience and consistent with future projections of District Heating CO₂ intensities as low as 0% to 20% by 2050:

- Several countries, including Norway, Sweden, and Iceland (which has zero CO₂ emissions due to geothermal heat), have *already* achieved DH CO₂ intensities less than 10% of the 300 g/kWh baseline (Werner, 2017).
- Heat Roadmap Europe (HRE) demonstrated a 2050 scenario reducing EU DH CO₂ emissions 74% below 2003 values (Connolly, 2014, p. 485). More recently, HRE forecasts between 86% and 100% de-carbonization of EU DH by 2050 (Paardekooper, HRE, 2018), though they have acknowledged that the biomass quantity used in the forecast may be unrealistically high (Paardekooper, personal communication, 2019).

- Munster articulated multiple scenarios for 100% renewable DH in Denmark by 2050 (Munster, 2018).
- A recent study showed that DH CO₂ emissions in selected Finnish and Polish systems could be cut 75% to 90%, and that 100% emissions reduction could be achieved at a higher cost with addition of CCS (Hast, 2018).

The global future adoption of Renewable District Heating is supported by multiple projections:

- Though IEA's forecasts of negative emissions are based on bioenergy combustion paired with CCS, clearly IEA is projecting very low DH CO₂ intensity for 2050 and beyond, even in the absence of CCS.
- Greenpeace, too, projects District Heating renewable energy adoption as high as 100% by 2050 (for both building and industrial applications) (Greenpeace, Energy Revolution, 2015, p. 317-318). The Greenpeace "Energy Revolution" scenario projects renewable penetration of 96% in 2050 and "Advanced Energy Revolution" projects 100% renewables, including 25% bioenergy, 41% solar, and 34% geothermal energy.

But confidence in these projections requires specificity in terms of which renewable resources will be applied where. And existing scenario projections vary in their specificity:

- IEA's projections emerge as one facet of comprehensive global energy scenarios that incorporate policy initiatives, primary and final energy balances across multiple end uses, corresponding CO₂ emissions forecasts, and many other factors and crosschecks. As one example, IEA forecasts that 2050 municipal solid waste (MSW) in cities, treated as a renewable resource, will almost equal DH demand (IEA ETP, 2016, p. 266).
- Greenpeace, however, in its scenarios, is not specific about how its projections would occur, especially, for example, the high proportion of site-specific geothermal energy.

Data supporting large DH CO₂ emissions reductions in China and Russia, the two countries with the largest DH specific CO₂ footprints, is less encouraging:

- Historically, between 1990 and 2015, European DH CO₂ emissions dropped about 40%, but global specific CO₂ emissions were flat, in large part due to increasing emissions from coal-fired DH in China (Werner, 2017).
- Looking toward the future of DH in China, Xiliang and Xiong demonstrated a strategy by which District Heating could cut building heating primary energy consumption by 60% by 2030 (reducing overall CO₂ emissions 3%) by shifting from DH Heat Plants to CHP (Xiliang, 2015; Xiong, 2015; Xiong, 2014). IEA notes Chinese plans to assess industrial excess heat recovery

potential for DH in 150 cities (IEA ETP, 2016, p. 118), and IEA’s recent report on China DH explores approaches for increasing renewable energy but makes no forecasts (IEA, District Energy Systems in China, 2017).

- Makarova demonstrates the increasing role of CHP in Russian District Heating, emphasizing efficiency, but does not focus on emissions (Makarova, 2015).

So, achieving 100% Renewable District Heating – or something very close to it – over the next 30 to 40 years is technically feasible and consistent with European DH experience over the *last* 40 years. It makes sense economically to reduce the waste that increases CO₂ emissions, and RDH is consistent with aggressive energy scenarios, such as IEA 2DS and B2DS. But 100% Renewable DH is far from a sure thing, especially in the regions with the highest CO₂ footprints today.

2.4.2 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 2.5, 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; District Heating continues to provide about 16% of all space heating delivered energy, 10% of which (1.6% of the TAM) is Renewable District Heating. District Heating CO₂ intensity is flat at the current level of 300 g/kWh. (see Section **Error! Reference source not found.**)

2.4.3 Project Drawdown Space Heating Delivered Energy Adoption Scenarios

Table 2.5 compares the three Project Drawdown scenarios (PDS) to the REF: “*Plausible*”, a reasonably ambitious case; “*Drawdown*”, an ambitious case where the target is explicitly to achieve drawdown; and “*Optimum*”, the maximum case considering resource limits and interdependencies of solution technologies.

Table 2.5 Renewable District Heating (RDH) Delivered Energy Adoption Scenarios

Project Drawdown Adoption Scenario	Reference / Baseline Cases	Conservative Cases	Ambitious Cases	Maximum Cases
	Reference Scenario	“Plausible” Scenario	“Drawdown” Scenario	“Optimum” Scenario
2014 to 2060 DH Delivered Energy Adoption Growth	Constant DH share; constant renewable share	Based on IEA ETP 2017 2DS DH Adoption	Based on IEA ETP 2017 B2DS DH Adoption	Beyond the IEA ETP 2017 B2DS DH Adoption
District Heating Share of Space Heating Delivered Energy TAM (%)				
2014	16%	16%	16%	16%
2020	16%	17%	17%	17%

Project Drawdown Adoption Scenario	Reference / Baseline Cases	Conservative Cases	Ambitious Cases	Maximum Cases
	Reference Scenario	“Plausible” Scenario	“Drawdown” Scenario	“Optimum” Scenario
2050	16%	18%	22%	23%
2060	16%	18%	21%	26%
CO2 Intensity Trajectory (g/kWh)				
2014	300	300	300	300
2020	300	300	300	300
2050	300	75 (linear from 2020 to 2060)	0 (100% renewable from 2050 on)	0 (100% renewable from 2040 on)
2060	300	0	0	0
Renewable DH Share of Space Heating Delivered Energy TAM (%)				
2014	1.6%	1.6%	1.6%	1.6%
2020	1.6%	2.5%	2.5%	3.8%
2050	1.6%	14%	21%	23%
2060	1.6%	18%	21%	26%

Plausible Scenario

In the Plausible Adoption Scenario, an ambitious case formulated to be consistent with the IEA ETP 2017 2DS scenario, District Heating adoption increases slowly from 16% of delivered energy TAM in 2014 to 18% in 2060. CO₂ intensity is flat at 300 g/kWh until 2020, as in the Plausible Scenario, and then drops linearly to zero g/kWh in 2060. Renewable DH grows from 1.6% of TAM in 2014 (10% of DH) to 18% (100% of District Heating) in 2060.

Drawdown Scenario

In the Drawdown Scenario, an aggressive case formulated to be consistent with the IEA ETP 2017 B2DS scenario, District Heating adoption increases more rapidly from 16% of delivered energy TAM in 2014 to 20% in 2060. CO₂ intensity is flat at 300 g/kWh until 2020, then drops linearly to zero g/kWh in 2050 and remains at zero through 2060. Renewable DH grows from 1.6% of TAM in 2014 to 20% of TAM (100% of District Heating) in 2060.

Optimum Scenario

In the Optimum Scenario, an aggressive but plausible “maximum” case formulated to go beyond the IEA ETP 2017 B2DS scenario, District Heating adoption increases more rapidly from 16% of delivered energy TAM in 2014 to 26% in 2060. CO₂ intensity is flat at 300 g/kWh until 2020, then drops linearly to

zero g/kWh in 2040, and remains at zero through 2060. Renewable DH grows from 1.6% of TAM in 2014 to 26% of TAM (100% of District Heating) in 2060.

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 Renewable District Heating 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 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 2.6.

To calculate the climate impacts of Renewable District Heating 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 CO₂ concentration change (in PPM equivalent). Then emissions reductions are calculated using the following equation:

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

where:

- $CO_2reduced$ is the CO₂-eq emissions reduction associated with the reduction in energy consumption in each PDS scenario (in metric tons).
- $Reduction\theta_{PDS}$ is the reduction in energy consumption (TWh).
- G_{ef} is the emissions factor (in t CO₂-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.
- F_{ef} is the fuel emissions factor (in t CO₂-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 2.6 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 2.6 Climate Inputs

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Global average REF Grid Emissions Factor	g CO ₂ e/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 ₂ e/TJ of fuel	87.04	87.04	8 including individual fuel emissions factors and shares	1

2.5.2 Financial Inputs

For in-building HVAC equipment – here termed “Conventional Technology” – first costs 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 technologies are weighted residential and commercial applications. The source for these values comes from the DOE, EIA, IEA, and IRENA. 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. The learning rate is primarily from Hayward & Graham (2013) and Koornneef (2007). The discount rate is sourced from data from the Survey of Consumer Finances from 1995 through 2010. These values are specific to the HVAC equipment evaluated in this report.

Table 2.7 presents the model inputs used to calculate the financial costs and savings annually for Conventional Technology: In-building HVAC:

Table 2.7 Financial Inputs for Conventional Technology: In-Building HVAC

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Installation Cost/ First Cost	US\$2014/ kW	89.71-305.89	197.80	30	7
First Cost Learning Rate	Percent	2.00%	2.00%	1	1
Annual Fixed Operating Cost	US\$2014/ kW/ yr	0.07-6.36	3.86	12	1
Annual Fuel Cost	US\$2014/ MWh	71.50	71.50	1	Derived from other inputs
Discount Rate for Future Cash flows	Percent	2.5%-8.2%	6.38%	20	3

For Renewable District Heating, first cost (measured in US\$2014/kW space heating delivered energy capacity) comprises the entire cost of the RDH system, including primary energy conversion, transmission, and distribution. Typically, the building owner owns in-building distribution and heat exchange equipment. Annual Variable Operating Costs (measured in US\$2014/kWh space heating delivered energy) relate to pumping energy, usage-related wear, purchase of biomass or municipal solid waste, and other expenses proportional to energy delivery. Fixed Operating Costs (measured in US\$2014/kW space heating delivered energy capacity) relate to non-usage-related maintenance, administrative, and other costs.

Table 2.8 presents the model inputs used to calculate the financial costs and savings annually for the Solution Technology: Renewable District Heating:

Table 2.8 Financial Inputs for the Solution Technology: Renewable District Heating

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
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Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Installation Cost/ First Cost	US\$2014/ kW	1,027-2,565	1,796	14	5
First Cost Learning Rate	Percent	2.00%	2.00%	1	1
Annual Variable Operating Cost	US\$2014/ MWh	0.2-9.2	4.7	2	3
Annual Fixed Operating Cost	US\$2014/ MW/ yr	570-55,730	28,153	1	3
Annual Fuel Cost	US\$2014/ MWh (th)*	N/A	N/A	N/A	Built into Annual Variable Operating Cost
Discount Rate for Future Cash flows	percent	2.5-8.2	6.38	20	3

With the range of labor costs, government policies, and construction standards, RDH First Cost varies widely around the world. Existing financial data on RDH is mostly limited to the OECD90 region, especially Western Europe. This is especially a challenge for Renewable DH, with its many different technologies and context-dependent cost variations.

2.5.3 Technical Inputs

Besides 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 of heat delivered by Renewable District Heating, an equivalent amount of heat energy would have been generated from conventional in-building fuel combustion (coal, oil, and natural gas only) or low-efficiency electric resistance or heat pump systems.

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 final energy. This is assumed to represent the average TWh of electricity used for each TWh (th) consumed for space heating (ideally this calculation would include efficiencies for each technology to convert to delivered

energy). Similarly, the fuel energy consumed is taken as the remaining energy consumed converted to TJ (the fuel energy input unit).

Table 2.9 presents energy-related technical inputs:

Table 2.9 Technical model inputs for Energy Consumption

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data-points (#)	Sources (#)
Electricity Consumed for Conventional Building Heating*	TWh (e)/ TWh(th)	0.61	0.61	1	Derived from other inputs
Electricity Consumed for Renewable DH Solution Building Heating*	TWh (e)/ TWh(th)	N/A	0	N/A	Assumed by Project Drawdown
Fuel consumed by Conventional Commercial Building*	TJ/ TWh(th)	1,403.4	1,403.4	1	Derived from other inputs
Fuel Consumption reduction Solution Compared to Conventional	Percent	100%	100%	1	Assumed by Project Drawdown

* Per unit *delivered energy*

Lifetime Variables

Several additional variables are necessary to calculate the financial benefits of Renewable District Heating. These include estimates for the life expectancy of both Conventional HVAC as well as RDH 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.

Lifetime-related variables are presented in Table 2.10.

Table 2.10 Technical Model Inputs for Usage and Lifetime

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data-points (#)	Sources (#)
Lifetime Capacity of conventional technology	TWh/TW	36,917-61,939	49,428	N/A	Derived from other Inputs
Average Annual Use of conventional technology	TWh/TW	14,34-3,468	2,451	20	3
Conventional Technology Lifetime	Years	6-30	19	20	3
Lifetime Capacity of solution technology	TWh/TW	114,168-156,341	135,254	N/A	Derived from other Inputs
Average Annual Use of solution technology	TWh/TW	2,769-8,502	5,636	3	2
RDH Solution Technology Lifetime	Years	20-30	24	5	3

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 the infrastructure required for the solution is available and in-place, necessary policies are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be 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: Renewable District Heating replaces only coal, oil, gas, electricity-based conventional space heating, and non-renewable District Heating (that is, no in-building biomass, solar or other renewables).

- Assumption 2:** Indirect emissions are not critical in this analysis (lack of data).
- Assumption 3:** Major published forecasts (IEA, USDOE, EIA, and others) of final energy demand over time, equipment efficiencies, especially heat pumps, and installed equipment shares are valid and self-consistent.
- Assumption 4:** 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.
- Assumption 5:** Implicitly, the Renewable District Heating adoption scenarios (which are based on analysis and projections from IEA, Greenpeace, and others) assume that the key success factors identified – which vary across scenarios – will be in place: Requisite government strategies and policies to foster Renewable DH; suitable high-energy-density urban locations; integrated energy strategies; adequate incremental innovation as Renewable DH systems evolve; access to suitable renewable resources, such as photovoltaics, municipal solid waste, biomass-fueled CHP, and geothermal.
- Assumption 6:** Evolution over the next 30 to 40 years toward Renewable District Heating in locations that have large existing District Heating implementations today, especially China, Russia, and Eastern Europe.

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 a prioritized sequence for each of space heating and cooling, lighting, cooking, and water heating (performed in four separate sequence chains). 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 solutions¹, and, for this, 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, the reduction factor is applied, scaled, and used to update the results in the lower priority solution model.

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

In addition to 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 demand²). Grid solutions are adjusted to remove the double counting as described in the Project Drawdown integration documentation.

2.8 LIMITATIONS/FURTHER DEVELOPMENT

The current analysis has the following limitations and opportunities for further development:

1. A major limitation of this study is the inclusion of multiple different renewable energy sources agglomerated into a single Solution – Renewable District Heating. IEA has done work in compiling coherent integrated energy future scenarios; Sven Werner and numerous collaborators have articulated and advanced District Heating state-of-the-art, as has Heat Roadmap Europe. But to confidently and convincingly estimate possible Renewable District Heating adoption, it would be valuable to have a much more granular and geographical-specific assessment of

¹ This can be interpreted as a single building with multiple efficiency technologies.

² Some solutions such as Electric Vehicles and High-Speed Rail increase the demand for electricity and reduce the demand for fuel.

renewable energy resources, costs, and future directions, as well as government commitments to use these renewable resources.

2. There is sparse data on the extent of District Heating in the United States and on the nature of District Heating systems in Russia and China (especially fuel boilers vs. CHP plants). These gaps limit the ability to quantify existing RDH implementation.
3. There is limited academic research on future directions of Renewable District Heating in Russia, China, and the US. These gaps limit the ability to forecast future adoption. A key aspect is lack of clarity on government policies and support in these regions.

3 RESULTS

3.1 ADOPTION

Table 3.1 presents the global adoption of the solution in key years of analysis in functional units and percent 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
Renewable District Heating	<i>TWh (th)</i>	149	988	1,451	1,725
	<i>(% TAM Delivered Energy)</i>	1.6%	13.8%	20.3%	24.1%

Figure 3.1 presents the world adoptions of Renewable District Heating in functional units for the three Project Drawdown scenarios.

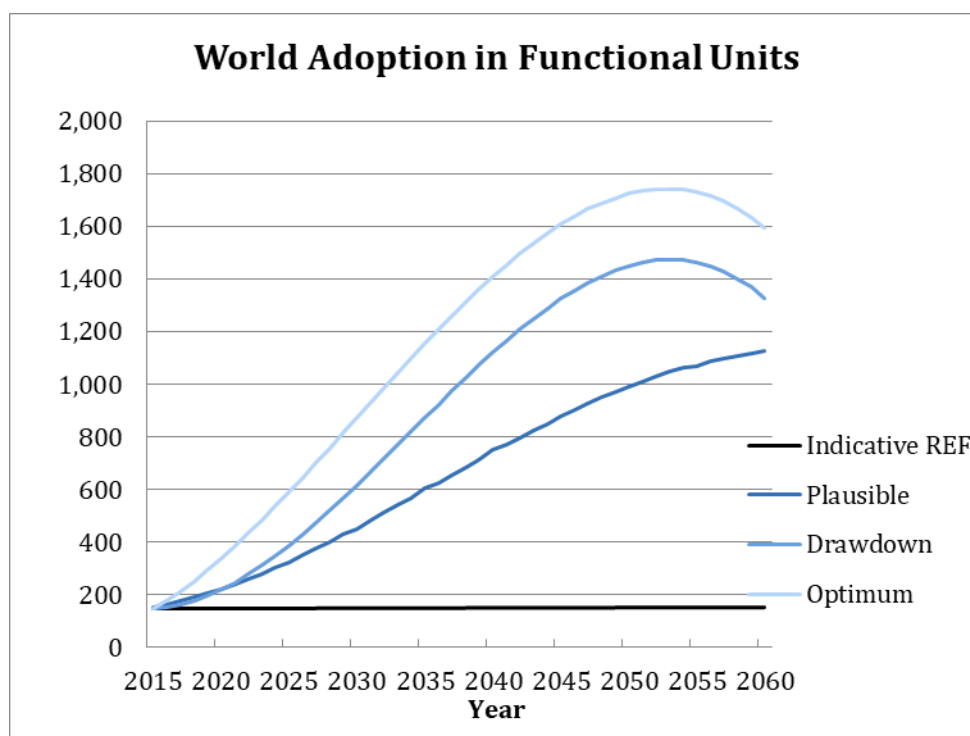


Figure 3.1 World Annual Adoption of Renewable District Heating in Functional Units 2020-2050

Figure 3.2 presents the global adoption of Renewable District Heating as a percent of the TAM for the three Project Drawdown scenarios.

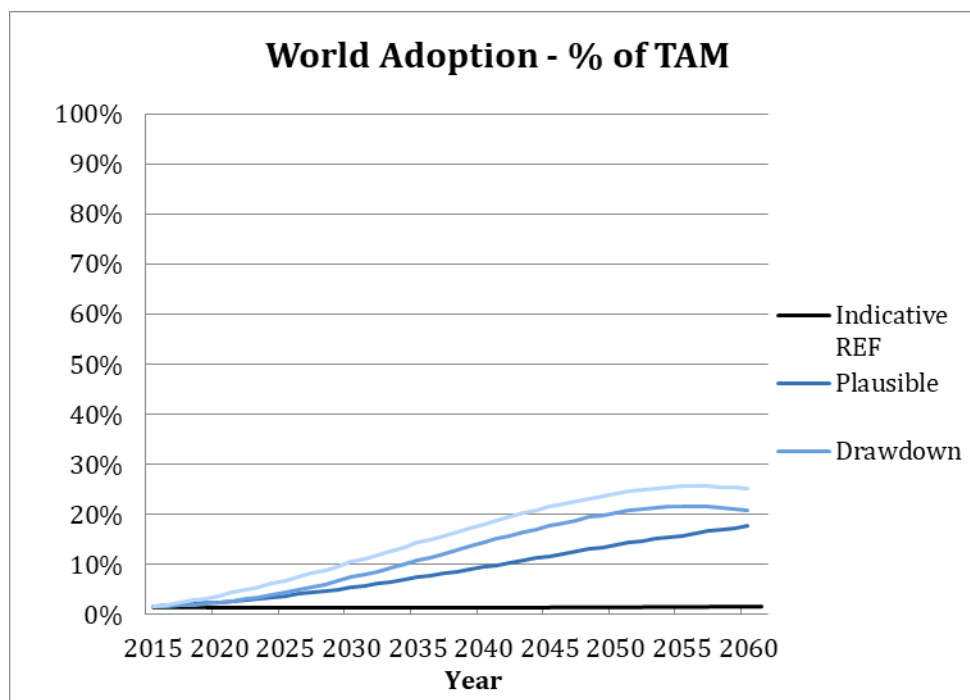


Figure 3.2 World Annual Adoption of Renewable District Heating as a Percent of TAM 2020-2050

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 6).

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	0.36	6.25	0.14	0.36
Drawdown	0.56	9.82	0.22	0.56
Optimum	0.68	13.34	0.34	0.68

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 CO₂-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	0.52	0.03
Drawdown	0.83	0.04
Optimum	1.11	0.05

Figure 3.3 presents the world GHG emissions reductions as a result of Renewable District Heating adoption for the three Project Drawdown scenarios.

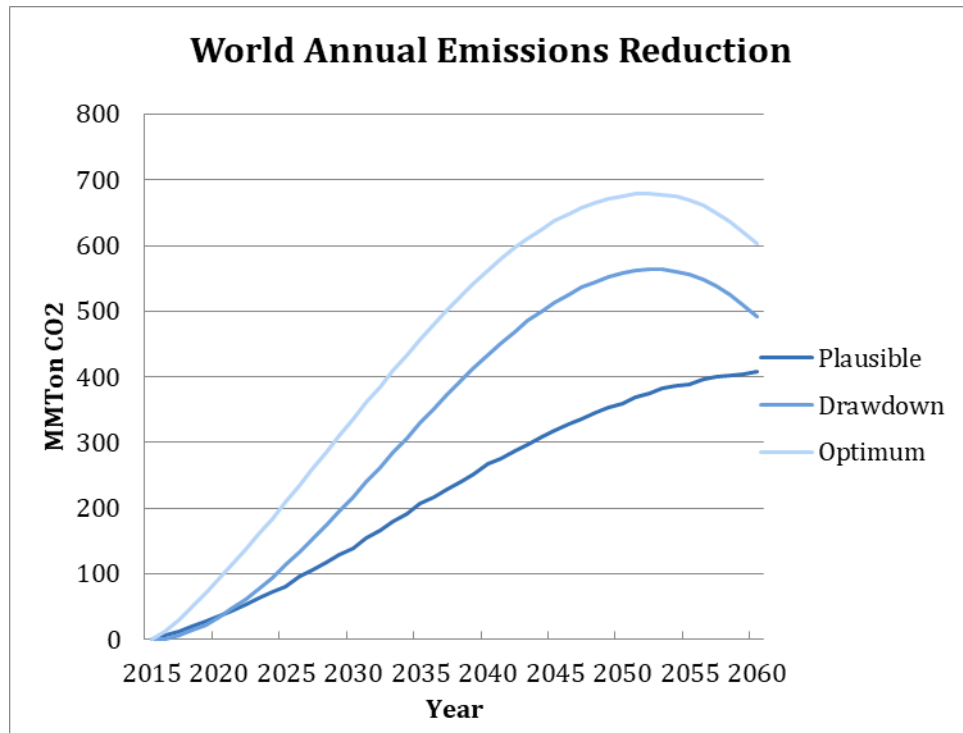


Figure 3.3. World Annual Greenhouse Gas Emissions Reduction

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	310.09	219.54	882.10	1,581.57	186.33
Drawdown	467.70	328.64	1,390.40	2,404.51	280.40
Optimum	609.20	428.16	1,876.44	3,150.87	405.37

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

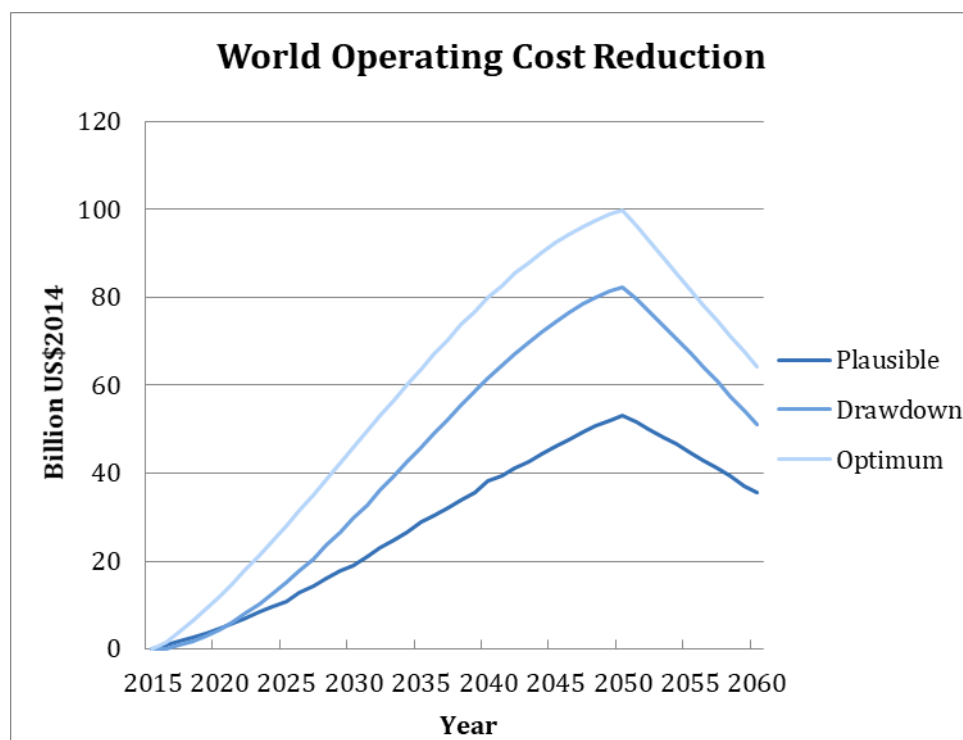


Figure 3.4 Net Profit Margin /Operating Costs Over Time

3.4 OTHER IMPACTS

A major option for future Renewable district heat generation, suggested by Scandinavian experience, is increased cogeneration via combined heat and power (CHP) plants burning biomass or municipal solid waste. This would be a high value application of organic material that cannot be recycled in some other way. It could also help to address the severe pollution that China has encountered from its coal-fired District Heating boilers.

Increased CHP would have major impact on electrical grid structure, driving it towards smaller, more urban generating plants, since the cogenerated heat could be transported only short distances to urban heating load centers. It would likely also increase grid resilience, since generating plants would be closer to electrical loads and more highly networked electrically.

4 DISCUSSION

District Heating (DH) offers unique potential for reducing GHG emissions by replacing individual fossil-fueled boilers and furnaces, and fossil-generated electric heat, with local renewable energy resources that are not accessible to individual buildings.

District Heating (DH) has evolved over the past 130+ years from fossil-fueled high-temperature steam-based systems to the increasingly-efficient renewably-fueled systems employed in some regions, especially Scandinavia, today. Moving forward, “4th Generation” DH systems will continue to reduce supply temperatures and replace fossil fuel primary energy with renewables, such as solar, biomass, geothermal, and “ambient energy”-based central heat pumps – this is Renewable District Heating (RDH).

RDH offers an important path for reducing GHG emissions in one of the world’s largest and most carbon-intensive energy sectors – building space heating. Widely adopted, RDH could provide over 20% of building space heating delivered energy by 2060. The result, detailed in Project Drawdown “*Drawdown*” Scenario, would be a cumulative (2020-205) reduction of 9.8 Gt of CO₂ emissions compared with the Reference Scenario. This would reduce atmospheric GHG concentrations by 0.83 PPM CO₂-equivalent in 2050. Lifetime operating cost savings would total \$2.4T from 2020 to 2050, with a lifetime cash flow savings NPV of \$0.28T. Applying RDH to building water heating would deliver similar scale benefits.

But there are challenges: Today, fossil fuel provides over 90% of all DH energy worldwide. DH networks in Russia and China, the two largest DH markets, and in major Eastern European countries with high adoption are almost 100% fossil-fueled. And District Heating, with its “economy of scope”, is economically constrained to high energy-density urban areas.

However, as Scandinavian experience over the last 40 years illustrates, it is possible to convert DH networks to renewable energy. And “high-density” is not a fixed number; the threshold for DH application can be expanded through innovation, and by adjusting financial, and political factors such as energy policy and strategy. What are the barriers and what needs to be done?

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

- Competition from low-cost CO₂-emitting fossil fuels and from high-efficiency HVAC equipment.
- High first cost for RDH and need for a community energy “utility” that requires in-ground installation, unlike modular in-building space heating equipment.
- Shrinking building space heating loads – which decrease energy density – as building thermal envelopes improve. Increasing urbanization is a counter trend.

- Need for coordination and planning with other energy resources: Relatively small-scale CHP is most economic for DH (low-temperature heat cannot be transported long distances economically) but small-scale CHP requires coordination with the electrical grid; traditionally-municipal energy resources such as municipal solid waste and heat from sewage water require government agreement; and DH can provide valuable thermal storage (in building thermal mass) to smoothen intermittent renewable electrical energy sources, such as solar and wind.

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

- Integrated government-backed energy strategy and policies incorporating:
 - A clear vision of energy consumption / GHG emissions objectives and strategy.
 - Policies that encourage RDH, including GHG emissions standards and incentives for cooperation between heat and electrical grids.
- High energy density heating load.
- Avoidance of “stranded asset” investments in fossil-related infrastructure and equipment.
- Ongoing Renewable District Heating technological innovation and implementation, especially:
 - Low-temperature (~50C) distribution networks.
 - Improved CHP plants based on municipal solid waste and biomass.
 - Development of central heat pump-boosted “ambient energy” sources.

4.1 LIMITATIONS

As discussed above, the limitations of Renewable District Heat include:

- Need for high density heating demand.
- Need for a renewable heating source with local proximity to urban demand.
- Need for well-coordinated national and local policy for energy supply, investment and pricing, urban planning, and related areas.
- Very high implementation cost that “locks-in” the community with the selected technology for several decades.

4.2 BENCHMARKS

Table 4.1 Benchmarks

Source and Scenario	Electricity Generation in 2050 (TWh)	Market Share in 2050 (%)	(Land) Per-Unit Impact	(Land) New Adoption	(Land) Mitigation Impact (i.e. Gt CO ₂ -eq in 2030)
Source /Scenario					
Source /Scenario					
Project Drawdown – Plausible Scenario (PDS1)					
Project Drawdown – Drawdown Scenario (PDS2)					
Project Drawdown – Optimum Scenario (PDS3)					

5 REFERENCES

- Averfalk, H. (2017). *Transformation Roadmap from High to Low Temperature District Heating Systems Annex XI final report*. IEA-DHC. Retrieved from <http://orbit.dtu.dk/files/142164425/Untitled.pdf>
- Averfalk, H., Ingvarsson, P., Persson, U., Gong, M., & Werner, S. (2017). Large heat pumps in Swedish district heating systems. *Renewable and Sustainable Energy Reviews*, 79, 1275–1284. <https://doi.org/10.1016/j.rser.2017.05.135>
- Averfalk, H., & Werner, S. (2018). Novel low temperature heat distribution technology. *Energy*, 145, 526–539. <https://doi.org/10.1016/j.energy.2017.12.157>
- Büchle, R., Kranzl, L., Müller, A., Hummel, M., Hartner, M., Deng, Y., & Bons, M. (2016). Comprehensive Assessment of the Potential for Efficient District Heating and Cooling and for High-Efficient Cogeneration in Austria. *International Journal of Sustainable Energy Planning and Management*, Vol 10 (2016)-. <https://doi.org/10.5278/ijsepm.2016.10.2>
- Connolly, D., Lund, H., Mathiesen, B. V., Werner, S., Möller, B., Persson, U., ... Nielsen, S. (2014). Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. *Energy Policy*, 65, 475–489. <https://doi.org/10.1016/j.enpol.2013.10.035>
- Dalla Rossa, A., Li, H., & Werner, S. (2014). *Toward 4th Generation District Heating*. IEA-DHC. Retrieved from https://www.iea-dhc.org/fileadmin/documents/Annex_X/IEA_Annex_X_Final_Report_2014_-_Toward_4th_Generation_District_Heating.pdf
- Danish Board of District Heating. (n.d.). DBDH. Retrieved January 25, 2019, from <https://dbdh.dk/>

- Danish Energy Agency. (2012). *Technology Data for Energy Plants*. Copenhagen.
- David, A., Mathiesen, B. V., Averfalk, H., Werner, S., & Lund, H. (2017). Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. *Energies*, 10(4), 578. <https://doi.org/10.3390/en10040578>
- Dulac, J. (2019). DHC Density, Personal Communication.
- Ericsson, K., & Werner, S. (2016). The introduction and expansion of biomass use in Swedish district heating systems. *Biomass and Bioenergy*, 94, 57–65. <https://doi.org/10.1016/j.biombioe.2016.08.011>
- Euroheat & Power. (n.d.). Country Profiles Archives. Retrieved January 24, 2019, from <https://www.euroheat.org/knowledge-hub/country-profiles/>
- Furbo, S., Fan, J., Perers, B., Kong, W., Trier, D., & From, N. (2015). Testing, Development and Demonstration of Large Scale Solar District Heating Systems. *Energy Procedia*, 70, 568–573. <https://doi.org/10.1016/j.egypro.2015.02.162>
- Gils, H. C. (2012). A GIS-based Assessment of the District Heating Potential in Europe (p. 13).
- Gils, H. C., Cofala, J., Wagner, F., & Schöpp, W. (2013). GIS-based assessment of the district heating potential in the USA. *Energy*, 58, 318–329. <https://doi.org/10.1016/j.energy.2013.06.028>
- Gong, M., & Werner, S. (2014). *District heating research in China* (p. 76).
- Gong, M., & Werner, S. (2017). Mapping energy and exergy flows of district heating in Sweden. *Energy Procedia*, 116, 119–127. <https://doi.org/10.1016/j.egypro.2017.05.060>
- Greenpeace. (2015). *Energy Revolution 2015*. Retrieved from <https://www.greenpeace.org/archive-international/Global/international/publications/climate/2015/Energy-Revolution-2015-Full.pdf>
- Hast, A., Syri, S., Lekavičius, V., & Galinis, A. (2018). District heating in cities as a part of low-carbon energy system. *Energy*, 152, 627–639. <https://doi.org/10.1016/j.energy.2018.03.156>
- Heat Roadmap Europe. (n.d.). Heat Roadmap Europe. Retrieved January 20, 2019, from <https://heatroadmap.eu/>
- IEA DHC. (n.d.). IEA District Heating and Cooling. Retrieved January 20, 2019, from <https://www.iea-dhc.org/index.php?id=287>, IEA/OECD, Paris.
- IEA Energy Technology Network. (2013). *IEA ETSAP Technology Brief E16 District Heating*. Retrieved from https://iea-etsap.org/E-TechDS/PDF/E16_DistrHeat_EA_Final_Jan2013_GSOK.pdf, IEA/OECD, Paris.
- ILF Consulting and AIT for Joint Research Centre, EU. (2017). Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU.
- International Energy Agency. (2011). *Combining Bioenergy with CCS* (p. 32), IEA/OECD, Paris.
- International Energy Agency. (2014). *Linking Heat and Electricity Systems: Co-generation and District Heating and Cooling Solutions for a Clean Energy Future*, IEA/OECD, Paris.
- International Energy Agency. (2016). *Energy Technology Perspectives 2016*, IEA/OECD, Paris.

- International Energy Agency. (2017a). *District Energy Systems in China* (p. 79), IEA/OECD, Paris.
- International Energy Agency. (2017b). *Energy Technology Perspectives 2017* (p. 443), IEA/OECD, Paris.
- International Energy Agency. (2018a). *Renewables 2018*, IEA/OECD, Paris.
- International Energy Agency. (2018b). *World Energy Balances 2018* (p. 762), IEA/OECD, Paris.
- Kemper, J. (2017). *Biomass with carbon capture and storage (BECCS/Bio-CCS)*. IEA GHG.
- Li, H., & Wang, S. J. (2014). Challenges in Smart Low-temperature District Heating Development. *Energy Procedia*, 61, 1472–1475. <https://doi.org/10.1016/j.egypro.2014.12.150>
- Lowe, R. (2011). Combined heat and power considered as a virtual steam cycle heat pump.
- Lund, H. (2018). *The Status of 4th Generation District Heating: Research and Results*. Presented at the 4th International Conference on Smart Energy Systems and 4th Generation District Heating. Retrieved from https://www.4dh.eu/images/HenrikLund_4DH_Conference_13November2018.pdf
- Lund, H., Connolly, D., & Mathiesen, B. V. (2011). Heating technologies for limiting biomass consumption in 100% renewable energy systems, 19.
- Lund, H., Østergaard, P. A., Chang, M., Werner, S., Svendsen, S., Sorknæs, P., Möller, B. (2018). The status of 4th generation district heating: Research and results. *Energy*, 164, 147–159. <https://doi.org/10.1016/j.energy.2018.08.206>
- Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th Generation District Heating (4GDH). *Energy*, 68, 1–11. <https://doi.org/10.1016/j.energy.2014.02.089>
- Lund, R., Østergaard, D. S., Yang, X., & Mathiesen, B. V. (2017). Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective. *International Journal of Sustainable Energy Planning and Management*, 12, 5–18. <https://doi.org/10.5278/ijsepm.2017.12.2>
- Makarova, A. S., Pankrushina, T. G., Urvantseva, L. V., & Khorshev, A. A. (2015). Combined heat and power in the draft of the new Russian energy strategy. *Thermal Engineering*, 62(6), 389–395. <https://doi.org/10.1134/S0040601515060051>
- Martinez, C. (2018). *District Energy In Cities*. Presented at the 4th International Conference on Smart Energy Systems and 4th Generation District Heating.
- Moller, B., & Werner, S. (2016). Quantifying the Potential for District Heating and Cooling in EU member States – WP 2 – Background Report 6. Retrieved January 20, 2019, from <https://heatroadmap.eu/wp-content/uploads/2018/09/STRATEGO-WP2-Background-Report-6-Mapping-Potenital-for-DHC.pdf>
- Munster, M., & Werner, S. (2018). *Chapter 11. District Heating and Cooling Systems Innovation Challenge* (p. 117). DTU International Energy Report.
- Paardekooper, S. (2018). *Heat Roadmap Europe 4: Quantifying the Impact of Low Carbon Heating and Cooling Roadmaps*. Aalborg University, Denmark. Retrieved from

http://vbn.aau.dk/files/288075507/Heat_Roadmap_Europe_4_Quantifying_the_Impact_of_Low_Carbon_Heating_and_Cooling_Roadmaps..pdf

Paardekooper, S. (2019). DHC HRE Forecast and Biomass - Personal Communication.

Poponi, D. (2016). *Nordic Energy Technology Perspectives 2016* IEA.

Quiquerez, L., Lachal, B., Monnard, M., & Faessler, J. (2017). The role of district heating in achieving sustainable cities: comparative analysis of different heat scenarios for Geneva. *Energy Procedia*, 116, 78–90. <https://doi.org/10.1016/j.egypro.2017.05.057>

Rämä, M. (n.d.). IEA DHC|CHP Brochure ANNEX XII. Retrieved January 23, 2019, from https://www.iea-dhc.org/fileadmin/documents/Annex_XII/180815_IEA_Brochure_ANNEX_XII_final_web.pdf

Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., Institute for Energy and Transport. (2013). *The JRC-EU-TIMES model: assessing the long-term role of the SET plan energy technologies*. Luxembourg: Publications Office. Retrieved from <http://bookshop.europa.eu/uri?target=EUB:NOTICE:LDNA26292:EN:HTML>

Spurr, M. (2002). *District Heating and Cooling: Environmental Technology for the 21st Century* (p. 8). IEA.

Spurr, M. (2014a). *IEA Annex X Final Report 2014 - Integrating Renewables*. IEA-DHC. Retrieved from https://www.iea-dhc.org/fileadmin/documents/Annex_X/IEA_Annex_X_Final_Report_2014_-_Integrating_Renewables.pdf

Spurr, M. (2014b). *IEA DHC 2014 - Integrating Renewables presentation. End of Annex Seminar*.

Trier, D. (2018). *Heat Roadmap Europe 4 - Business Cases and Business Strategies to Encourage Market Uptake*. Aalborg University, Denmark. Retrieved from http://vbn.aau.dk/files/290997081/HRE4_D7.16_vbn.pdf

U.S Department of Energy. (2018). Updated Buildings Sector Appliance and Equipment Costs and Efficiency, 740.

US Energy Information Agency. (2018). *U.S. District Energy Services Market Characterization* (p. 71).

US Energy Information Agency. (n.d.). How much carbon dioxide is produced when different fuels are burned? - FAQ - U.S. Energy Information Administration (EIA). Retrieved February 7, 2019, from <https://www.eia.gov/tools/faqs/faq.php?id=73&t=11>

Werner, S. (2017a). District heating and cooling in Sweden. *Energy*, 126, 419–429. <https://doi.org/10.1016/j.energy.2017.03.052>

Werner, S. (2017b). International review of district heating and cooling. *Energy*, 137, 617–631. <https://doi.org/10.1016/j.energy.2017.04.045>

Werner, S. (2017c). *World DH status and Transformation Roadmap for 4GDH*. Presented at the 3rd International Conference On Smart Energy Systems and 4Th Generation District Heating.

Werner, S. (2019). DHC Density Personal Communication Sven Werner.

- Winterscheid, C., Dalenbäck, J.-O., & Holler, S. (2017). Integration of solar thermal systems in existing district heating systems. *Energy*, 137, 579–585. <https://doi.org/10.1016/j.energy.2017.04.159>
- Xiliang, Z. (2015). *The Role of Innovative District Heating Solutions in China's Energy Revolution*.
- Xiong, W. (2014). *Heat Roadmap China*.
- Xiong, W., Wang, Y., Mathiesen, B. V., Lund, H., & Zhang, X. (2015). Heat roadmap China: New heat strategy to reduce energy consumption towards 2030. *Energy*, 81, 274–285. <https://doi.org/10.1016/j.energy.2014.12.039>

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

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

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

Cumulative First Cost – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis

period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Delivered Energy – the energy transferred to or from a space for space heating or space cooling purposes. Traditional technologies often were based on consuming fuels to provide this (e.g. oil burning or running electricity through a high resistance heating element). But newer technologies can transfer heat from other places (such as outside air or water), which weakens the link between energy consumption and delivered energy.

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 CO₂e/kWh.

Final Energy – the energy consumed (of coal, oil, gas, electricity etc.) in providing for a particular end use (space heating, cooling, lighting, water heating etc).

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.

Heat Pump – a technology that can move heat against natural heat flow directions (that is, to hotter places) in order to provide space heating or space cooling functions. Most cooling systems, like air-conditioning units, operate with similar technology, but “heat pump” often refers to heating systems that extract heat from outside air to heat buildings.

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.

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

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

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

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.

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

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

