Explanatory Note on the District Heating Emissions Calculation Model

Project Number: 52230-001
May 2020

PRC: Xiangtan Low-Carbon Transformation Sector Development Program

MEMORANDUM

TO: Asian Development Bank, Xiangtan Program Management Office
FROM: Rachael Jonassen, PhD
DATE: May 24, 2020
RE: Emissions Estimates for District Heating in Yuhu and Yuetang Districts, Xiangtan County

1. Overview

This memorandum accompanies a report to ADB summarizing projected impacts of Low Carbon City Development in the municipality (county) of Xiangtan, China. The report summarizes each of the project-based and policy-based actions that will be undertaken as a result of the requested loan and indicates the ways in which those actions can be expected to influence the trajectory of GHG emissions over the lifetime of the loan (to 2045). This memo details assumptions and calculations used to estimate the impacts of the district heating network powered by industrial surplus heat (ISH) from the Xiangtan Iron & Steel Co., Ltd. of Hunan Valin ("Steel Mill") in Yuhu and Yuetang Districts.

The baseline scenario represents a 'Business as Usual" (BAU) case where the composition of the buildings and heating sources do not change from today (2020). Under the BAU scenario, all factors that could be influenced by the project-based and policy-based loans are held constant at 2020 values. Only the external factor of population changes in the BAU scenario. The "ADB Scenario" represents the case where each project-based and policy-based action is implemented over time. The ADB Scenario examines the effect of three policy-based actions. These actions are:

1. Action plan on the promotion of district energy systems in Xiangtan (institutional reforms to promote comprehensive waste heat recovery for district energy systems; mandatory connection to district energy systems; market- and consumption-based tariff for district energy systems)
2. District energy zone mapping in Xiangtan with indication of clean energy/waste heat sources
3. Technical standards on district energy systems in Xiangtan

Policy-based actions are designed to occur in two tranches with different implementation dates and the effects of policies on human behavior are also phased over time as they reach greater numbers of the relevant population.

Projected impacts of project-based and policy-based actions related to the building sector are plotted against energy sector emission trajectories for two scenarios, referred to as "Worst Case" and "Best Case" scenarios. Emission trajectories for the BAU and Goal scenarios are derived from two Integrated Assessment Models (IAMs) as reported by the IPCC in the Fifth Assessment. These IAMs provide a global representation of emission trajectories that are used by the international climate change community. At the global scale, these are called Representative Concentration Pathways (RCPs). IAMs create projections of global emissions by socio-economic modeling using a grid-cell discretization of the Earth.

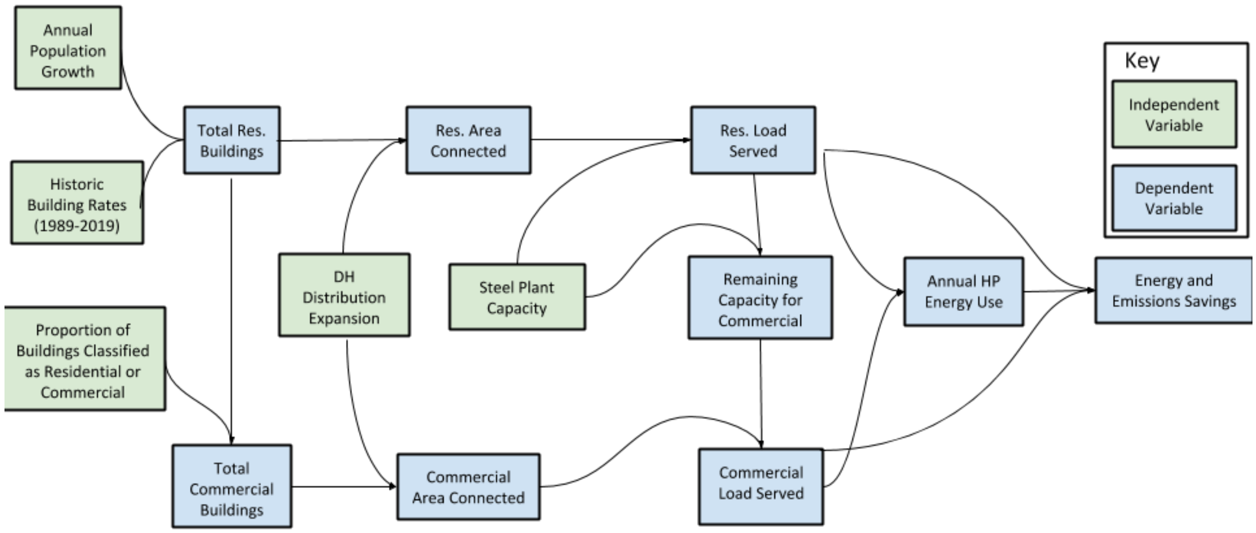
Emission estimates from project and policy-based actions in Xiangtan are compared to solutions derived from the IAM grid cell containing Xiangtan for the RCP 8.5 scenario, developed by the MESSAGE modeling system, and the RCP 2.6 scenario, developed by the IMAGE modeling system. This grid cell does not contain Changsha or other major Chinese cities; therefore, it is reasonable to believe that the results primarily represent emissions due to activities in Xiangtan. For the energy sector, RCP 8.5 represents the "Worst Case" scenario, in which the global economy follows a pathway of emissions close to that China is now following as it continues to expand the use of coal and oil as energy sources, while RCP 2.6 represents the "Best Case" scenario, exhibiting an early peaking of GHG emissions followed by a rapid decline. These are the two most extreme RCP scenarios; thus, movement from one to the other represents the most ambitious goal.

2. Assumptions

1. The District Energy Zone includes all of YH and YT (see Appendix, Figure A1 and A2).

2. Due to existing district heating service in YH and YT, only a certain percentage of the total built environment can be serviced by DH from the Steel Mill. This percentage is estimated from visual inspection of Figure A3 (see Appendix).
3. No additional emissions are created from use of waste heat from the Steel Mill for the district heating network except those created by the electric-powered heat pump used to expand the service area. Alternative uses of ISH, such as electricity generation, are not considered.
4. The build-out of the district heating modification in the Steel Mill is completed in one stage by the user-specified date for each scenario. Major components are the heat exchanger unit(s) and (in some scenarios) a heat pump. It is believed the first stage of modifications (heat exchanger only) could be completed by 2022, while installation of a heat pump would not occur before 2026 (see Section 4. User-Defined Parameters).
5. "Commercial" and "public/ commercial" buildings include all non-residential buildings.
6. Building quantities assume no future change in ratios of residential to commercial/public buildings, numbers of residents per household, number of household units per residential building, and population growth rate into the future. Projected building rates reflect only what is needed to meet this additional housing demand and maintain constant ratios of residential and commercial/ public buildings in the overall building stock. This method may underestimate actual increases in commercial building space evidenced in yearbook data from YH + YT (XT PMO 2020).
7. Build-out of the distribution system (pipeline transmission system and residential connections), is a separate effort from the plant modifications. The distribution system is extended to residential and commercial buildings according to a logistic growth model that assumes construction will begin in 2020.
8. Distribution system costs would be borne by a private enterprise, which would execute a contract with the Steel Mill to use the available steam.
9. The pipeline transmission system would extend under the XT River to service homes in Yuhu.
10. All residential units and commercial building space within a building are connected to DH service simultaneously. Residential and commercial buildings are assumed to be randomly distributed throughout the Steel Mill service area. Residential buildings heated with electric heat pumps and natural gas boilers are assumed to be randomly distributed throughout the Steel Mill service area.
11. Base load indices for both residential and commercial space heating are equal to one-half of peak load indices, and are assumed to remain constant from 2020-2045 (see Section 4. User-Defined Inputs).
12. In scenarios where the HP is used to expand the serviceable area, the energy cost of running the HP assumes the HP has variable operation capabilities and will only operate when necessary to meet demand unmet by the heat exchanger. Emissions associated with HP operation assume the HP is powered by electricity from the Xiangtan electric grid. Electricity generation from ISH is not considered, although this may be a viable source of low-emission electricity to power the HP (see Li et al. 2016).
13. HP performance characteristics are estimated from reported characteristics of similar HP systems for DH applications (see Section 4. User-Defined Parameters).
14. Average equivalent heating hours at base load and peak load service are assumed to be the same for both residential and commercial service.
15. DH service available for commercial space heating each year assumes demand from connected commercial buildings is only served after demand from connected residential buildings is completely satisfied. This opens the possibility that as more residential area is connected to the system, the excess space heating capacity for commercial may decrease from year to year, such that commercial buildings receiving energy from the DH system in one year may be "cut off" in the next year. This may raise further questions about the rationality of investing in the distribution infrastructure or any building modifications that may be necessary.
16. Impacts of policies affecting residential and commercial energy use are assumed to be additive, and any synergistic effects of DH, green building, and/or BEMS policies are not modeled in emission reduction estimates.

3. Logical Flow



4. User-Defined Parameters

Parameter	Value	Equation	Data Source	Explanation
L (%)	100%	*Eq. 1*		*Maximum percentage of residential/ commercial buildings connected to DH system* Logistic growth parameter indicating maximum extent of DH service within Steel Mill service area.
k (%)	150%	*Eq. 1*		*DH Build-out Logistic growth rate* Parameter chosen to reflect DH distribution network build-out scenario connecting all buildings within the Steel Mill service area by 2028, based on evidence from Li et al. (2016) of substantial prior experience with DH infrastructure in northern China.
t_0 (year)	2,024	*Eq. 1*		*DH Build-out Midpoint year* Parameter chosen to reflect DH distribution network build-out scenario connecting all buildings within the Steel Mill service area by 2028, based on evidence from Li et al. (2016) of substantial prior experience with DH infrastructure in northern China.
$N(2019)_{XT}$ *(persons)*	3,050,000	*Eq. 2*	XT Health and H Comm.	*XT Population, 2019* Total estimated XT County population in 2019, used as the starting value for population estimates 2020-2045.
r (persons/yr)	12,500	*Eq. 2*	XT Health and H Comm	*XT Population growth rate* Annual population growth in XT County, 2019-2045, assuming linear growth.
p_{YH+YT} *(%)*	33.5%	*Eq. 2*	XT City Assessment Report	*Proportion of population in YH+YT* Assumed to remain constant 2019-2045. Population of YH+YT assumed to grow proportional to population of XT County
p_{SA}*(%)*	30%	*Eq. 2*	Figure A3	*Percent of YT + YH Residential Heating Demand in Steel Mill Service Area* Visual inspection of maps of current and planned DH service indicated roughly 30% of YH+YT area could still benefit from DH service from the Steel Mill

p_{res} (%)	64%	*Eq. 4*	Yi et al. (2018), p 21	*Percentage of buildings classified as residential* Used to extrapolate total number of buildings and number of public/ commercial buildings in YH+YT
p_{com}(%)	36%	*Eq. 4*	Yi et al. (2018), p 21	*Percentage of buildings classified as public/ commercial* Assumed that all buildings are classified as either residential or public/ commercial
ζ_{pph} *(persons/ household)*	3.10	*Eq. 3*	Xiangtan 2018 Year book	*Population per household* XT GHG Inventory (2015), Ch. 2, City Profile lists 2.84 for YT and 2.86 for YH for an average value of 2.85. ADB Survey of households in August 2019 asked (Q. 2) "How many members in your household?" The average of 406 responses is 3.52. The Xiangtan 2018 Year book reports the value for urban as 3.10 for the year 2017.
ζ_{hpb} *(units/ building)*	120	*Eq. 3* *Eq. 5*	Gálvez and Cheshmehzangi (2015), p 5	*Residential units per building* From 2000-2007, roughly 80% of new urban residential development in China consisted of mid-rise (4-8 floors) and high-rise (up to 34 floors) buildings. A typical model in the City of Guangzhou included a mix of buildings with 4-8 units per floor. We assume an average of 6 units per floor, 20 floors per building.
ζ_{aph} *(m^2/ household)*	138.88	*Eq. 5*	XT PMO	*Per household living space, 2019* ADB household survey (Q 22) asked "What is the status of your home?" The average of 406 responses is 112.88. The XT 2018 Year book reports the value (per person) for urban as 44.8 for the year 2017, or 138.88m2 per household, assuming 3.10 people/household.
ζ_{apb} *(m^2/ building)*	4,500	*Eq. 6*	Shaofang Li (2020)	*Average floor area of a commercial/ public building* Estimated from average data from 200 buildings retrofitted with BEMS as part of the project-based component of the loan.
t_{HX} *(year)*	2,022	*Eq. 7*	XT PMO	*Year DH power becomes available* Assumed year of Steel Plant retrofit for DH service with HX only
t_{HP} *(year)*	2,026	*Eq. 8*	XT PMO	*Year HP becomes available* Assumed year of Steel Plant retrofit for DH service with HP
$T_{S,1}$ (^oC)	50	*Eq. 7* *Eq. 8*	Shaofang Li (2020)	*Steel Plant supply water temperature* Estimated supply water temperatures for two HX and HP systems at the Steel Mill. Used in determining total energy recovered for DH
$T_{S,2}$ (^oC)	75	*Eq. 7* *Eq. 8*		
$T_{R,HX,1}$ (^oC)	45	*Eq. 7*	Shaofang Li (2020)	*Steel Plant return water temperature after HX* Estimated return water temperatures for two HX systems at the Steel Mill. Used in determining total energy recovered for DH.
$T_{R,HX,2}$ (^oC)	45	*Eq. 7*		
$T_{R,HP,1}$ (^oC)	10	*Eq. 8*	Shaofang Li (2020)	*Steel Plant return water temperature after HP* Estimated return water temperatures for two HP systems at the Steel Mill. Used in determining total energy recovered for DH.
$T_{R,HP,2}$ (^oC)	10	*Eq. 8*		
Q_1 *(m^3/hr)*	30,000	*Eq. 7* *Eq. 8*	Shaofang Li (2020)	*HX/HP fluid flow rate* Estimated fluid flow rate in two HX or HP systems at the Steel Mill. Used in determining total energy recovered for DH. Units were inferred from dimensional analysis of calculations provided by Shaofang Li.
Q_2 *(m^3/hr)*	15,000	*Eq. 7* *Eq. 8*		

*U (MW/ (m^3*K))*	0.001163	*Eq. 7* *Eq. 8*	Shaofang Li (2020), Gyllenbok (2018) p. 133	*Overall heat transfer coefficient* Units were inferred from dimensional analysis of calculations provided by Shaofang Li and published values for the heat transfer coefficient of water ($1m^3H_2O*K*hr^{-1}$ = 1,000 $kgH_2O*K*hr^{-1}$ = 1,000 $kcal*hr^{-1}$ = 1,163 $W*m^{-3}*K^{-1}$= 0.001163 $MW*m^{-3}*K^{-1}$)
$I_{res,B}$ *(MW/ m^2)*	0.000025	*Eq. 9* *Eq. 10*	Shaofang LI (2020)	*Residential heating load index, base load* Assumed to equal ½ heating load index at peak load, based on calculations for residential energy demand from Shaofang Li (2020)
$I_{res,P}$ *(MW/ m^2)*	0.000050	*Eq. 11* *Eq. 12*	Shaofang Li (2020)	*Residential heating load index, peak load* Units were inferred from dimensional analysis of calculations provided by Shaofang Li. Li et al. (2016) reported an average residential peak load index of 49 W/m2 in northern China.
$I_{com,B}$ *(MW/ m^2)*	0.000030	*Eq. 13* *Eq. 14*	Shaofang Li (2020)	*Commercial heating load index, base load* Assumed to equal ½ heating load index at peak load, based on calculations for residential energy demand from Shaofang Li (2020). Units were inferred from dimensional analysis of calculations provided by Shaofang Li.
$I_{com,P}$ *(MW/ m^2)*	0.000060	*Eq. 15* *Eq. 16*	Shaofang LI (2020)	*Commercial heating load index, peak load* Units were inferred from dimensional analysis of calculations provided by Shaofang Li.
HH_B *(hr/ yr)*	2,160	*Eq. 17* *Eq. 18* *Eq. 47* *Eq. 48* *Eq. 49* *Eq. 50*	Shaofang Li (2020)	*Heating hours per year, base load* Used for both residential and commercial base load.
HH_P *(hr/yr)*	1,310	*Eq. 19* *Eq. 20* *Eq. 53* *Eq. 54* *Eq. 55* *Eq. 56*	Shaofang Li (2020)	*Heating hours per year, peak load* Used for both residential and commercial peak load
TL (%)	5.00%	*Eq. 25* *Eq. 36*	Shaofang LI (2020)	*Transmission loss* Expected energy losses if equivalent power delivered by DH network were transmitted as electricity. Used to estimate BAU power consumption relative to DH service power consumption.
κ_G *(MWh/ Nm^3)*	0.009	*Eq. 26* *Eq. 28* *Eq. 37* *Eq. 39*	Shaofang Li (2020)	*Gas thermal value* Used to compare express electricity and gas consumption in comparable units
$p_{G,res}$ *(%)*	11%	*Eq. 26* *Eq. 27*	XT PMO	*Share of gas (residential)* Percentage of homes using gas boilers for heating, estimated from ADB Household Survey (2019)
η_{boiler}*(%)*	95%	*Eq. 26* *Eq. 37*	Shaofang Li (2020)	*Gas boiler efficiency* Estimated average efficiency of building-integrated natural gas boiler for heating
$COP_{ASHP,res}$	2.00	*Eq. 27*	Shaofang Li (2020)	*COP of air source heat pump (residential)* Assumed coefficient of performance for building-integrated air source heat pump for both residential and commercial heating

$\eta_{DH\ pump}$ (MWh/ MWh)	0.0005	Eq. 28 Eq. 32 Eq. 39 Eq. 43	Shaofang Li (2020)	*DH water pump efficiency* (MWh electric power consumed to pump water through the DH network per MWh power delivered, assumed to be invariable with size of DH network)
EF_E (tCO_2e/ MWh)	0.462	Eq. 32 Eq. 43 Eq. 52 Eq. 58	ADB	*Emission factor for electricity* From Central China Grid
EF_G (tCO_2e/ Nm^3)	0.00196	Eq. 32 Eq. 43	Shaofang Li (2020)	*Emission factor for natural gas*
$p_{G,com}$ (%)	0.00%	Eq. 37 Eq. 38	XT PMO	*Share of gas (commercial)* Percentage of commercial using gas boilers for heating
$COP_{ASHP,com}$	2.00	Eq. 38	Shaofang Li (2020)	*COP of air source heat pump* Assumed coefficient of performance for building-integrated air source heat pump for both residential and commercial heating
COP_{HP}	4.00	Eq. 47 Eq. 48 Eq. 49 Eq. 50 Eq. 53 Eq. 54 Eq. 55 Eq. 56	David et al. (2017)	*COP of HP* The Heat Roadmap Europe (HRE) study developed a database on the status of DH using large-scale electric heat pumps in Europe. The survey examined existing capacity of 149 large-scale electric heat pump units with thermal output capacity exceeding 1 MW, only one HP system in Slovakia was comparable in terms of both heat source and input/ output temperatures, and the COP for this system was chosen for all analyses. Sensitivity analyses of HP COP are included in the Appendix.
Carbon price (2020USD /tCO_2e)	$20.00			*Carbon price (2020USD /tCO2e)* Used in valuation of emission reductions to inform cost-benefit analyses.

5. Calculations

The following sections describe methods used in estimating energy and GHG impacts of policy-based actions for the promotion of green building standards in Yuhu and Yuetang Districts. Formulas in the following sections are represented in the "Summary Equations" tab of the spreadsheet titled "District Heating Emissions Calculations - Xiangtan ADB Output 4, 13 May 2020". The results of these calculations have been validated against earlier calculations performed in other tabs of the same spreadsheet, and a thorough dimensional analysis of all tabs of the spreadsheet was conducted May 13, 2020 to confirm dimensional agreement of all calculations.

5.1. District Heating Distribution System Expansion

Expansion of the DH network within the service area of the Steel Mill is modeled with user-defined logistic growth parameters. XT demographic data is used to estimate population and residential housing demand growth 2020-2045 assuming linear population growth. DH connection rates are applied to housing projections to estimate the number of residential buildings and total residential space heating area served by DH from the Steel Mill each year. Assuming the relative proportion of residential and public/ commercial buildings within the Steel Mill service area matches the proportion in YH+YT and this proportion remains constant into the future, the estimated number of residential buildings is extrapolated to estimate the number of commercial buildings within the Steel Mill service area. DH connection rates are applied equally to residential and commercial buildings, assuming random dispersion of each building type throughout the service area, to estimate commercial buildings and commercial space heating area connected each year. Estimates of the number of buildings connected are rounded to the nearest whole number.

$$y(i) = \frac{L}{1+exp(k*(t_0-t_i))} \quad for\ t_i > 2020,\ 0\ otherwise \qquad \text{Equation 1}$$

Where:

$y(i) = Percentage\ of\ total\ units\ within\ the\ steel\ plant\ service\ area\ connected\ to\ DH\ System\ by\ year\ i$ (%)
$L = maximum\ percentage$ (%)
$k = logistic\ growth\ rate$ (%)
$t_0 = midpoint\ year$
$t_i = year\ i$

$$N(i)_{SA} = (N(i-1)_{XT} + r) * p_{YH+YT} * p_{SA} \quad \text{Equation 2}$$

$$B(i)_{res,DH} = y(i) * N(i)_{SA} * \frac{1}{\zeta_{pph}} * \frac{1}{\zeta_{hpb}} \quad \text{Equation 3}$$

$$B(i)_{com,DH} = y(i) * B(i)_{res,SA} * \frac{p_{com}}{p_{res}} \quad \text{Equation 4}$$

$$A(i)_{res,DH} = B(i)_{res,DH} * \zeta_{hpb} * \zeta_{aph} \quad \text{Equation 5}$$

$$A(i)_{com,DH} = B(i)_{com,DH} * \zeta_{apb} \quad \text{Equation 6}$$

Where:

$B(i)_{res,DH} = total\ number\ of\ residential\ buildings\ connected\ to\ DH\ network\ by\ year\ i$
$N(i)_{SA} = population\ of\ H\ and\ YT\ within\ Steel\ Mill\ service\ area\ in\ year\ i$
$N(i)_{XT} = population\ of\ XT\ in\ year\ i$
$r = annual\ XT\ population\ growth\ (persons/year)$
$p_{YH+YT} = percentage\ of\ XT\ population\ living\ in\ H\ and\ YH$ (%)
$p_{SA} = percentage\ of\ YH\ and\ YT\ population\ living\ within\ Steel\ Mill\ service\ area$ (%)
$B(i)_{res,SA} = total\ number\ of\ residential\ buildings\ within\ Steel\ Mill\ service\ area\ in\ year\ i$
$B(i)_{com,DH} = total\ number\ of\ commercial\ buildings\ connected\ to\ DH\ network\ by\ year\ i$
$A(i)_{res,DH} = total\ residential\ space\ heating\ area\ connected\ to\ DH\ network\ by\ year\ i$
$A(i)_{com,DH} = total\ commercial\ space\ heating\ area\ connected\ to\ DH\ network\ by\ year\ i$
$p_{com} = percentage\ of\ building\ stock\ classified\ as\ commercial\ in\ YH\ and\ YT$ (%)
$p_{res} = percentage\ of\ building\ stock\ classified\ as\ residential\ in\ YH\ and\ YT$ (%)
$\zeta_{pph} = average\ population\ per\ household\ (persons/household)$
$\zeta_{hbp} = average\ number\ of\ households\ per\ residential\ building\ (households/building)$
$\zeta_{aph} = average\ living\ space\ area\ per\ household\ (m^2/household)$
$\zeta_{apb} = average\ floor\ area\ per\ commercial\ building\ (m^2/building)$

5.2. DH Service Capacity

Capacity of DH system is estimated for four scenarios (base load service without heat pump, peak load service without heat pump, base load service with heat pump, and base load service without heat pump) based on supply temperature and return temperature of water used in the DH network, flow rate, and residential heating load index for base load and peak load service. Parameter values and calculations were provided by Shaofang Li (2020) for two heat pump and heat exchanger systems with different supply temperatures and flow rates, then summed to estimate total energy recovered by the system. Serviceable residential area at base load and peak load is then calculated with an assumed residential heating load index. Average equivalent heating hours at base load and peak load service are used to estimate total power supply capacity in each scenario.

$$E(i)_{HX} = \sum_{1}^{j}((T_{S,j} - T_{R,HX,j}) * Q_j) * U \quad for\ i \geq t_{HX},\ 0\ otherwise \quad \text{Equation 7}$$

$$E(i)_{HP} = \sum_{1}^{j}((T_{S,j} - T_{R,HP,j}) * Q_j) * U \quad for\ i \geq t_{HP},\ 0\ otherwise \quad \text{Equation 8}$$

Where:

$E_{HX} = Energy\ recovered\ by\ heat\ exchanger\ (MW)$
$E_{HP} = Energy\ recovered\ by\ heat\ pump\ and\ heat\ exchanger\ (MW)$
$T_{S,j} = Supply\ water\ temperature\ for\ HP\ or\ HX\ system\ j$ (^{O}C)

$T_{R,HX,j}$ = Return water temperature after HX in system j (^{o}C)
$T_{R,HP,j}$ = Return water temperature after HP in system j (^{o}C)
Q_j = fluid flow rate in HP or HX system j (m^3/hr)
U = fluid heat transfer coefficient ($\frac{MW}{m^3K}$)
t_{HX} = year Steel Mill is outfitted with HX and DH power becomes available
t_{HP} = year Steel Mill is outfitted with HP

$$A_{res,B,HX} = \frac{E_{HX}}{I_{res,B}}$$ *Equation 9*

$$A_{res,B,HP} = \frac{E_{HP}}{I_{res,B}}$$ *Equation 10*

$$A_{res,P,HX} = \frac{E_{HX}}{I_{res,P}}$$ *Equation 11*

$$A_{res,P,HP} = \frac{E_{HP}}{I_{res,P}}$$ *Equation 12*

$$A_{com,B,HX} = \frac{E_{HX}}{I_{com,B}}$$ *Equation 13*

$$A_{com,B,HP} = \frac{E_{HP}}{I_{com,B}}$$ *Equation 14*

$$A_{com,P,HX} = \frac{E_{HX}}{I_{com,P}}$$ *Equation 15*

$$A_{com,P,HP} = \frac{E_{HP}}{I_{com,P}}$$ *Equation 16*

Where:

$A_{res,B,HX}$ = maximum residential serviceable area at base load service, with heat exchanger only (m^2)
$A_{res,B,HP}$ = maximum residential serviceable area at base load service, with heat pump (m^2)
$A_{res,P,HX}$ = maximum residential serviceable area at peak load service, with heat exchanger only (m^2)
$A_{res,P,HP}$ = maximum residential serviceable area at peak load service, with heat pump (m^2)
$I_{res,B}$ = residential heat load index at base load service (MW/m^2)
$I_{res,P}$ = residential heat load index at peak load service (MW/m^2)

$A_{com,B,HX}$ = maximum commercial serviceable area at base load service, with heat exchanger only (m^2)
$A_{com,B,HP}$ = maximum commercial serviceable area at base load service, with heat pump (m^2)
$A_{com,P,HX}$ = maximum commercial serviceable area at peak load service, with heat exchanger only (m^2)
$A_{com,P,HP}$ = maximum commercial serviceable area at peak load service, with heat pump (m^2)
$I_{com,B}$ = commercial heat load index at base load service (MW/m^2)
$I_{com,P}$ = commercial heat load index at peak load service (MW/m^2)

$$P_{B,HX} = E_{HX} * HH_B$$ *Equation 17*

$$P_{B,HP} = E_{HP} * HH_B$$ *Equation 18*

$$P_{P,HX} = E_{HX} * HH_P$$ *Equation 19*

$$P_{P,HP} = E_{HP} * HH_P$$ *Equation 20*

Where:

$P_{B,HX}$ = power supply capacity at base load service, with heat exchanger only (MWh)
$P_{B,HP}$ = power supply capacity at base load service, with heat pump (MWh)
$P_{P,HX}$ = power supply capacity at peak load service, with heat exchanger only (MWh)
$P_{P,HP}$ = power supply capacity at peak load service, with heat pump (MWh)
HH_B = equivalent heating hours, base load (hr)
HH_P = equivalent heating hours, peak load (hr)

5.3. Space Heating Capacity for Commercial

XT PMO has indicated build-out of the DH distribution network will prioritize connection of residential buildings. However, as build-out of the distribution network is expected to lag retrofit of the Steel Mill, based on evidence from build-out of the other DH systems in northern China (Li et al. 2016), simultaneous connection of residential and commercial buildings in the same area was explored as a means of utilizing heating capacity of the Steel Mill more effectively and efficiently. After satisfying all connected residential heating demand in a given year, the remaining space heating capacity for commercial buildings was calculated as the excess space heating capacity at residential base or peak load service multiplied by the ratio of total commercial serviceable area to total residential serviceable area in each scenario.

$$A(i)_{com,B,HX} = (A_{res,B,HX} - A(i)_{res,DH}) * \frac{A_{com,B,HX}}{A_{res,B,HX}} \quad for\ A_{res,B,HX} \geq A(i)_{res,DH},\ 0\ otherwise \quad \text{Equation 21}$$

$$A(i)_{com,B,HP} = (A_{res,B,HP} - A(i)_{res,DH}) * \frac{A_{com,B,HP}}{A_{res,B,HP}} \quad for\ A_{res,B,HP} \geq A(i)_{res,DH},\ 0\ otherwise \quad \text{Equation 22}$$

$$A(i)_{com,P,HX} = (A_{res,P,HX} - A(i)_{res,DH}) * \frac{A_{com,P,HX}}{A_{res,P,HX}} \quad for\ A_{res,P,HX} \geq A(i)_{res,DH},\ 0\ otherwise \quad \text{Equation 23}$$

$$A(i)_{com,P,HP} = (A_{res,P,HP} - A(i)_{res,DH}) * \frac{A_{com,P,HP}}{A_{res,P,HP}} \quad for\ A_{res,P,HP} \geq A(i)_{res,DH},\ 0\ otherwise \quad \text{Equation 24}$$

Where:

$A(i)_{com,B,HX}$ = remaining space heating capacity for commercial at base load in year i, with HX only (m^2)
$A(i)_{com,B,HP}$ = remaining space heating capacity for commercial at base load in year i, with HP (m^2)
$A(i)_{com,P,HX}$ = remaining space heating capacity for commercial at peak load in year i, with HX only (m^2)
$A(i)_{com,P,HP}$ = remaining space heating capacity for commercial at peak load in year i, with HP (m^2)

5.4. Residential Energy Savings and CO_2 Emission Reductions

Total potential residential energy savings and CO_2 emission reductions were calculated by Shaofang Li (2020) for each service scenario, assuming the full residential service capacity of the DH network is realized. Energy consumption in each DH scenario compared net energy produced (total energy capacity of the HX or HX and HP system, less electricity consumed by pumps used to transmit water throughout the DH distribution network) and electricity or natural gas that would otherwise be consumed by building-integrated gas boilers and air-source heat pumps in the BAU scenario (equivalent to total energy supply capacity of the HX or HX and HP system, less transmission losses). The proportion of residential buildings using gas boilers was estimated from the XT PMO household survey (2019). Total energy and emissions savings were normalized by the maximum serviceable area to determine average savings per unit area served, and the annual energy and emissions savings are calculated as the residential area connected each year multiplied by the energy and emissions savings per unit area. Equations described for the scenario with base load service, HX implementation are repeated for all scenarios.

$$P(BAU)_{res,B,HX} = P_{B,HX} * (1 - TL) \quad \text{Equation 25}$$

$$P(BAU)_{G,res,B,HX} = P(BAU)_{res,B,HX} * \frac{1}{\kappa_G} * \frac{1}{\eta_{boiler}} * p_{G,res} \quad \text{Equation 26}$$

$$P(BAU)_{E,res,B,HX} = P(BAU)_{res,B,HX} * \frac{(1-p_{G,res})}{COP_{ASHP,res}} \quad \text{Equation 27}$$

$$\Delta P_{res,B,HX} = P(BAU)_{G,res,B,HX} * \kappa_G + P(BAU)_{E,res,B,HX} - P_{B,HX} * \eta_{DH\ pump} \quad \text{Equation 28}$$

$$\delta P_{res,B,HX} = \frac{\Delta P_{res,B,HX}}{A_{res,B,HX}} \quad for\ A_{res,B,HX} > 0,\ 0\ otherwise \quad \text{Equation 29}$$

$$\Delta P(i)_{res,B,HX} = \delta P_{res,B,HX} * A(i)_{res,DH} \quad for\ A(i)_{res,DH} \leq A_{res,B,HX} \quad \text{Equation 30}$$

$$\Delta P(i)_{res,B,HX} = \delta P_{res,B,HX} * A_{res,B,HX} \quad for\ A(i)_{res,DH} > A_{res,B,HX} \quad \text{Equation 31}$$

Where:

$\Delta P_{res,B,HX}$ = total potential annual energy savings from residential heating compared to BAU (MWh)

$\delta P_{res,B,HX}$ = annual residential energy savings per square meter (base load, HX scenario) (MWh/m^2)
$\Delta P(i)_{res,B,HX}$ = annual energy savings from residential heating (base load, HX scenario) in year i (MWh)
$P(BAU)_{res,B,HX}$ = total annual residential energy use for heating, BAU (base load, HX scenario) (MWh)
$P(BAU)_{G,res,B,HX}$ = annual residential natural gas consumption for heating, BAU(base load, HX scenario) (Nm^3)
$P(BAU)_{E,res,B,HX}$ = annual residential electricity consumption for heating, BAU (base load, HX scenario) (MWh)
TL = transmission losses (%)
κ_G = gas thermal value (MWh/Nm^3)
$p_{G,res}$ = percentage of residential buildings heating with gas boilers (%)
$COP_{ASHP,res}$ = building integrated air source heat pump coefficient of performance (MWh/MWh)
η_{boiler} = gas boiler efficiency (%)
$\eta_{DH\ pump}$ = DH water pump efficiency (MWh consumed/MWh delivered)

$$\Delta CO_{2,res,B,HX} = P(BAU)_{G,res,B,HX} * EF_G + (P(BAU)_{E,res,B,HX} - P_{B,HX} * \eta_{DH\ pump}) * EF_E \qquad \text{Equation 32}$$

$$\delta CO_{2,res,B,HX} = \frac{\Delta CO_{2,res,B,HX}}{A_{res,B,HX}} \quad \text{for } A_{res,B,HX} > 0,\ 0 \text{ otherwise} \qquad \text{Equation 33}$$

$$\Delta CO_{2,res,B,HX}(i) = \delta CO_{2,res,B,HX} * A(i)_{res,DH} \quad \text{for } A(i)_{res,DH} \le A_{res,B,HX} \qquad \text{Equation 34}$$

$$\Delta CO_{2,res,B,HX}(i) = \delta CO_{2,res,B,HX} * A_{res,B,HX} \quad \text{for } A(i)_{res,DH} > A_{res,B,HX} \qquad \text{Equation 35}$$

Where:

$\Delta CO_{2,res,B,HX}$ = total potential annual CO_2 emission savings from residential heating (base load, HX) (tCO_2e)
$\delta CO_{2,res,B,HX}$ = annual residential CO_2 emission savings per square meter (base load, HX) (tCO_2e/m^2)
$\Delta CO_{2,res,B,HX}(i)$ = annual CO_2 emission savings from residential heating in year i (base load, HX) (tCO_2e)
EF_G = CO_2 emission factor for natural gas (tCO_2e/Nm^3)
EF_E = CO_2 emission factor for electricity (tCO_2e/MWh)

5.5. Commercial Energy Savings and CO_2 Emission Reductions

A calculation procedure analogous to that provided by Shaofang Li (2020) for total potential commercial energy and emission savings for each service scenario, assuming the full commercial service capacity of the DH network is realized. Energy consumption in each DH scenario compared net energy produced (total energy capacity of the HX or HX and HP system, less electricity consumed by pumps used to transmit water throughout the DH distribution network) and electricity or natural gas that would otherwise be consumed by building-integrated gas boilers and air-source heat pumps in the BAU scenario (equivalent to total energy capacity of the system less 5% transmission losses). The proportion of commercial buildings using gas boilers was estimated to be effectively zero. Total energy and emissions savings were normalized by the maximum serviceable area to determine average savings per unit area served, and the annual energy and emissions savings are calculated as the commercial area served each year (the lesser of commercial area connected and commercial space heating capacity in each year for each scenario) multiplied by the energy and emissions savings per unit area. Equations depicted below for base load service, HX implementation are repeated for all scenarios.

$$P(BAU)_{com,B,HX} = P_{B,HX} * (1 - TL) \qquad \text{Equation 36}$$

$$P(BAU)_{G,com,B,HX} = P(BAU)_{com,B,HX} * \frac{1}{\kappa_G} * \frac{1}{\eta_{boiler}} * p_{G,com} \qquad \text{Equation 37}$$

$$P(BAU)_{E,com,B,HX} = P(BAU)_{com,B,HX} * \frac{(1 - p_{G,com})}{COP_{ASHP,com}} \qquad \text{Equation 38}$$

$$\Delta P_{com,B,HX} = P(BAU)_{G,com,B,HX} * \kappa_G + P(BAU)_{E,com,B,HX} - P_{B,HX} * \eta_{DH\ pump} \qquad \text{Equation 39}$$

$$\delta P_{com,B,HX} = \frac{\Delta P_{com,B,HX}}{A_{com,B,HX}} \quad \text{for } A_{com,B,HX} > 0,\ 0 \text{ otherwise} \qquad \text{Equation 40}$$

$$\Delta P(i)_{com,B,HX} = \delta P_{com,B,HX} * A(i)_{com,DH} \quad \text{for } A(i)_{com,DH} \le A(i)_{com,B,HX} \qquad \text{Equation 41}$$

$$\Delta P(i)_{com,B,HX} = \delta P_{com,B,HX} * A_{com,B,HX} \quad \text{for } A(i)_{com,DH} > A(i)_{com,B,HX} \qquad \text{Equation 42}$$

Where:

$\Delta P_{com,B,HX}$ = total potential annual energy savings from commercial heating compared to BAU (MWh)
$\delta P_{com,B,HX}$ = annual commercial energy savings per square meter (base load, HX scenario) (MWh/m^2)
$\Delta P(i)_{com,B,HX}$ = annual energy savings from commercial heating (base load, HX scenario) in year i (MWh)
$P(BAU)_{com,B,HX}$ = total annual commercial energy use for heating, BAU (base load, HX scenario) (MWh)
$P(BAU)_{G,com,B,HX}$ = annual commercial natural gas consumption for heating, BAU(base load, HX scenario) (Nm^3)
$P(BAU)_{E,com,B,HX}$ = annual commercial electricity consumption for heating, BAU (base load, HX scenario) (MWh)
$p_{G,com}$ = percentage of commercial buildings heating with gas boilers (%)
$COP_{ASHP,com}$ = building integrated air source heat pump coefficient of performance (MWh/MWh)

$$\Delta CO_{2,com,B,HX} = P(BAU)_{G,com,B,HX} * EF_G + (P(BAU)_{E,com,B,HX} - P_{B,HX} * \eta_{DH\ pump}) * EF_E \quad \text{Equation 43}$$

$$\delta CO_{2,com,B,HX} = \frac{\Delta CO_{2,com,B,HX}}{A_{com,B,HX}} \quad for\ A_{com,B,HX} > 0,\ 0\ otherwise \quad \text{Equation 44}$$

$$\Delta CO_{2,com,B,HX}(i) = \delta CO_{2,com,B,HX} * A(i)_{com,DH} \quad for\ A(i)_{com,DH} \leq A(i)_{com,B,HX} \quad \text{Equation 45}$$

$$\Delta CO_{2,com,B,HX}(i) = \delta CO_{2,com,B,HX} * A(i)_{com,B,HX} \quad for\ A(i)_{com,DH} > A(i)_{com,B,HX} \quad \text{Equation 46}$$

Where:

$\Delta CO_{2,com,B,HX}$ = total potential annual CO_2emission savings from commercial heating (base load, HX) (tCO_2e)
$\delta CO_{2,com,B,HX}$ = annual commercial CO_2 emission savings per square meter (base load, HX) (tCO_2e/m^2)
$\Delta CO_{2,com,B,HX}(i)$ = annual CO_2 emission savings from commercial heating in year i (base load, HX) (tCO_2e)

5.6. Energy and Emissions Cost of Heat Pump

Energy used to run the HP is calculated by comparing energy extracted by the HP and HX system to energy extracted by the HX alone to determine the energy directly extracted by the HP (in scenarios where the HP is not utilized, this difference is equal to zero). This assumes that the HP is selectively used to increase energy extraction above what is extracted by the heat exchanger, based on evidence of continuously variable HP operation in large-scale DH systems from Averfalk et al. (2017). Emissions associated with HP operation assume the HP is powered by electricity from the Xiangtan electric grid. Residential and commercial area served is calculated as the lesser of total serviceable area and area connected. For scenarios with HP operation, total annual energy savings and emission reductions are calculated as the combined savings and reductions of residential and commercial heating less the energy and emission cost of the HP each year. A secondary assumption, where the HP is only utilized to deliver the marginal increase in service over capacity without the HP, was tested and documented in the sensitivity analysis (see Appendix). In the absence of information on the COP of the HP used for the XT Steel Mill, the COP for a similar large-scale DH HP system in Europe was determined from the literature (see Appendix).

$$P(i)_{HP,B,res} = A(i)_{res,DH} * \frac{(E_{HP}-E_{HX})*HH_B}{A_{res,B,HP}} * \frac{1}{COP_{HP}} \quad for\ A_{res,B,HP} > 0\ and\ A(i)_{res,DH} \leq A_{res,B,HP} \quad \text{Equation 47}$$

$$P(i)_{HP,B,res} = A_{res,B,HP} * \frac{(E_{HP}-E_{HX})*HH_B}{A_{res,B,HP}} * \frac{1}{COP_{HP}} \quad for\ A_{res,B,HP} > 0\ and\ A(i)_{res,DH} > A_{res,B,HP} \quad \text{Equation 48}$$

$$P(i)_{HP,B,com} = A(i)_{com,DH} * \frac{(E_{HP}-E_{HX})*HH_B}{A_{com,B,HP}} * \frac{1}{COP_{HP}} \quad for\ A_{com,B,HP} > 0\ and\ A(i)_{com,DH} \leq A(i)_{com,B,HP} \quad \text{Equation 49}$$

$$P(i)_{HP,B,com} = A(i)_{com,B,HP} * \frac{(E_{HP}-E_{HX})*HH_B}{A_{com,B,HP}} * \frac{1}{COP_{HP}} \quad for\ A_{com,B,HP} > 0\ and\ A(i)_{res,DH} > A(i)_{com,B,HP} \quad \text{Equation 50}$$

$$P(i)_{HP,B} = P(i)_{HP,B,res} + P(i)_{HP,B,com} \quad \text{Equation 51}$$

$$CO_{2,HP,B}(i) = P(i)_{HP,B} * EF_E \quad \text{Equation 52}$$

$$P(i)_{HP,P,res} = A(i)_{res,DH} * \frac{(E_{HP}-E_{HX})*HH_P}{A_{res,P,HP}} * \frac{1}{COP_{HP}} \quad for\ A_{res,P,HP} > 0\ and\ A(i)_{res,DH} \leq A_{res,P,HP} \quad \text{Equation 53}$$

$$P(i)_{HP,P,res} = A_{res,P,HP} * \frac{(E_{HP}-E_{HX})*HH_P}{A_{res,P,HP}} * \frac{1}{COP_{HP}} \quad for\ A_{res,P,HP} > 0\ and\ A(i)_{res,DH} > A_{res,P,HP} \quad \text{Equation 54}$$

$$P(i)_{HP,P,com} = A(i)_{com,DH} * \frac{(E_{HP}-E_{HX})*HH_P}{A_{com,P,HP}} * \frac{1}{COP_{HP}} \quad for\ A_{com,P,HP} > 0\ and\ A(i)_{com,DH} \le A(i)_{com,P,HP}$$
Equation 55

$$P(i)_{HP,P,com} = A(i)_{com,P,HP} * \frac{(E_{HP}-E_{HX})*HH_P}{A_{com,P,HP}} * \frac{1}{COP_{HP}} \ for\ A_{com,P,HP} > 0\ and\ A(i)_{res,DH} > A(i)_{com,P,HP}$$ *Equation 56*

$$P(i)_{HP,P} = P(i)_{HP,P,res} + P(i)_{HP,P,com}$$ *Equation 57*

$$CO_{2,HP,P}(i) = P(i)_{HP,P} * EF_E$$ *Equation 58*

Where:

$P(i)_{HP,B}$ = annual power consumed by heat pump for base load service in year i (MWh)
$P(i)_{HP,B,res}$ = annual power consumed by heat pump for residential base load service in year i (MWh)
$P(i)_{HP,B,com}$ = annual power consumed by heat pump for commercial base load service in year i (kWh)
$P(i)_{HP,P}$ = annual power consumed by heat pump for peak load service in year i (kWh)
$P(i)_{HP,P,res}$ = annual power consumed by heat pump for residential peak load service in year i (kWh)
$P(i)_{HP,P,com}$ = annual power consumed by heat pump for commercial peak load service in year i (kWh)
COP_{HP} = HP coefficient of performance (MWh/MWh)
$CO_{2,HP,B}(i) = CO_2$ annual emissions associated with heat pump use for base load service in year i (tCO_2e)
$CO_{2,HP,P}(i) = CO_2$ annual emissions associated with heat pump use for peak load service in year i (tCO_2e)

5.7. Optimal HP Implementation

Total annual emission reductions achieved at either base load servicer peak load service are compared for scenarios with HP and without HP each year from 2020-2045. Any emission reduction benefit of utilizing the HP to serve a greater portion of the population is calculated by comparing the emission reductions achieved base load and peak load scenarios to determine the year of optimal HP implementation, if applicable. Optimal service level is then determined by comparing the emission reductions achieved in the optimized base load and peak load service scenarios.

$$\Delta P(i)_{B,HX} = \Delta P(i)_{res,B,HX} + \Delta P(i)_{com,B,HX}$$ *Equation 59*

$$\Delta P(i)_{B,HP} = \Delta P(i)_{res,B,HP} + \Delta P(i)_{com,B,HP} - P(i)_{HP,B}$$ *Equation 60*

$$\Delta P(i)_{P,HX} = \Delta P(i)_{res,P,HX} + \Delta P(i)_{com,P,HX}$$ *Equation 61*

$$\Delta P(i)_{P,HP} = \Delta P(i)_{res,P,HP} + \Delta P(i)_{com,P,HP} - P(i)_{HP,P}$$ *Equation 62*

$$\Delta CO_{2,B,HX}(i) = \Delta CO_{2,res,B,HX}(i) + \Delta CO_{2,com,B,H}(i)$$ *Equation 63*

$$\Delta CO_{2,B,HP}(i) = \Delta CO_{2,res,B,HP}(i) + \Delta CO_{2,com,B,HP}(i) - CO_{2,HP,B}(i)$$ *Equation 64*

$$\Delta CO_{2,P,HX}(i) = \Delta CO_{2,res,P,HX}(i) + \Delta CO_{2,com,P,H}(i)$$ *Equation 65*

$$\Delta CO_{2,P,HP}(i) = \Delta CO_{2,res,P,HP}(i) + \Delta CO_{2,com,P,HP}(i) - CO_{2,HP,P}(i)$$ *Equation 66*

Where:
$\Delta P(i)_{B,HX}$ = annual net energy savings (base load, HX scenario) in year i (MWh)
$\Delta P(i)_{B,HP}$ = annual net energy savings (base load, HP scenario) in year i (MWh)
$\Delta P(i)_{P,HX}$ = annual net energy savings (peak load, HX scenario) in year i (MWh)
$\Delta P(i)_{P,HP}$ = annual net energy savings (peak load, HP scenario) in year i (MWh)
$\Delta CO_{2,B,HX}(i)$ = annual net CO_2 emission reduction (base load, HX scenario) in year i (tCO_2e)
$\Delta CO_{2,B,HP}(i)$ = annual net CO_2 emission reduction (base load, HP scenario) in year i (tCO_2e)
$\Delta CO_{2,P,HX}(i)$ = annual net CO_2 emission reduction (peak load, HX scenario) in year i (tCO_2e)
$\Delta CO_{2,P,HP}(i)$ = annual net CO_2 emission reduction (peak load, HP scenario) in year i (tCO_2e)

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Appendix

A1. ABBREVIATIONS AND ACRONYMS

ADB	Asian Development Bank
CO_2	Carbon Dioxide
tCO_2e	Tonnes of Carbon Dioxide Equivalents
DH	District Heating
EF	Emission Factor
GHG	Greenhouse Gas
BAU	Business As Usual
ISH	Industrial Surplus Heat
XT	Xiangtan
XTMG	Xiangtan Municipal Government
XT PMO	Xiangtan Program Management Office
YT	Yuetang District
YH	Yuhu District
HX	Heat Exchanger
HP	Heat Pump
ASHP	Air Source Heat Pump
COP	Coefficient of Performance
Nm^3	cubic meter of gas, measured at standard temperature and pressure
MW	Megawatt
MWh	Megawatt-hour
kW	Kilowatt
kWh	Kilowatt-hour
^{O}C	Degrees Celsius

Figure A1: Yuhu District (outlined in red)

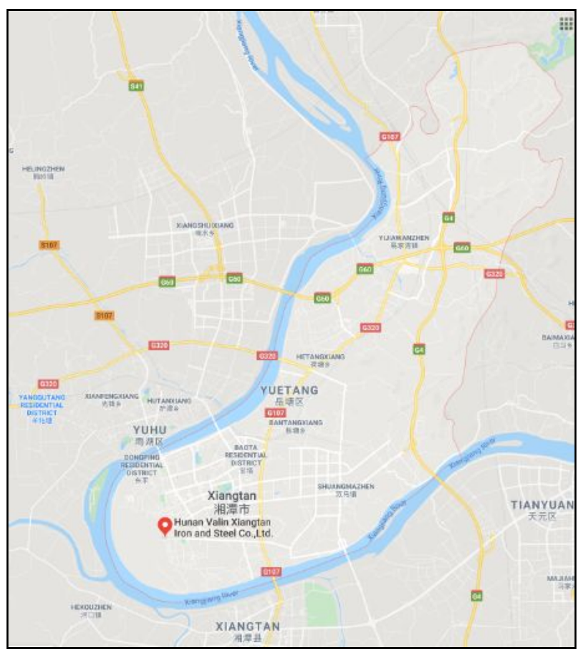

Figure A2: Yuetang District (outlined in purple)

Figure A3: Existing district heating systems

A2. Sensitivity Analyses

A2.1. Heat Pump Energy Demand

Under Assumption 1, the annual energy and emission cost of operating the HP assumes that the HP is only "turned on" when the residential area served exceeds the area that could be served without the HP, and the energy cost is calculated from this marginal energy delivered by the HP. This energy cost is converted to an emission cost using the emission factor for electricity. Total emissions savings in these scenarios is calculated as the sum of emissions savings from residential and commercial heating less the emissions cost of the HP.

$$P(i)_{HP,B} = P(i)_{HP,res,B} + P(i)_{HP,com,B} \quad \textit{Equation A1}$$

$$P(i)_{HP,res,B} = (A(i)_{res,HP,B} - A(i)_{res,HX,B}) * \frac{E_{HP}}{A_{res,B,HP}} * \frac{1}{COP_{HP}} \quad \textit{Equation A2}$$

$$P(i)_{HP,com,B} = (A(i)_{com,HP,B} - A(i)_{com,HX,B}) * \frac{I_{com,B}}{I_{res,B}} * \frac{E_{HP}}{A_{res,B,HP}} * \frac{1}{COP_{HP}} \quad \textit{Equation A3}$$

$$P(i)_{HP,P} = P(i)_{HP,res,P} + P(i)_{HP,com,P} \quad \textit{Equation A4}$$

$$P(i)_{HP,res,P} = (A(i)_{res,HP,P} - A(i)_{res,HX,P}) * \frac{E_{HP}}{A_{res,P,HP}} * \frac{1}{COP_{HP}} \quad \textit{Equation A5}$$

$$P(i)_{HP,com,P} = (A(i)_{com,HP,P} - A(i)_{com,HX,P}) * \frac{I_{com,P}}{I_{res,P}} * \frac{E_{HP}}{A_{res,P,HP}} * \frac{1}{COP_{HP}} \quad \textit{Equation A6}$$

$$\Delta P(i) = \Delta P(i)_{res} + \Delta P(i)_{com} - P(i)_{HP} \quad \textit{Equation A7}$$

$$CO_{2,HP}(i) = P(i)_{HP} * EF_{E} \quad \textit{Equation A8}$$

$$\Delta CO_2(i) = \Delta CO_{2,res}(i) + \Delta CO_{2,com}(i) - CO_{2,HP}(i) \quad \textit{Equation A9}$$

$A(i)_{res,extra\ served,B}$ = *additional residential space heating area served at base load with the HP* (m^2)
$A(i)_{comm,extra\ served,B}$ = *additional commercial space heating area served at base load with the HP* (m^2)
$A(i)_{res,extra\ served,P}$ = *additional residential space heating area served at peak load with the HP* (m^2)
$A(i)_{comm,extra\ served,P}$ = *additional commercial space heating area served at peak load with the HP* (m^2)

Under Assumption 2, once the HP is added to the Steel Mill DH system, any DH service is assumed to use the HP, and the associated energy cost is associated with all energy delivered by the DH system. This method was chosen for the final analysis.

$$P(i)_{HP,B} = P(i)_{HP,res,B} + P(i)_{HP,com,B} \quad \textit{Equation A10}$$

$$P(i)_{HP,res,B} = A(i)_{res,B} * \frac{E_{HP}}{A_{res,B,HP}} * \frac{1}{COP_{HP}}$$ *Equation A11*

$$P(i)_{HP,com,B} = A(i)_{com,B} * \frac{I_{com,B}}{I_{res,B}} * \frac{E_{HP}}{A_{res,B,HP}} * \frac{1}{COP_{HP}}$$ *Equation A12*

$$P(i)_{HP,P} = P(i)_{HP,res,P} + P(i)_{HP,com,P}$$ *Equation A13*

$$P(i)_{HP,res,P} = A(i)_{res,P} * \frac{E_{HP}}{A_{res,P,HP}}$$ *Equation A14*

$$P(i)_{HP,com,P} = A(i)_{com,P} * \frac{I_{com,P}}{I_{res,P}} * \frac{E_{HP}}{A_{res,P,HP}} * \frac{1}{COP_{HP}}$$ *Equation A15*

$$\Delta P(i) = \Delta P(i)_{res} + \Delta P(i)_{com} - P(i)_{HP}$$ *Equation A16*

$$CO_{2,HP}(i) = P(i)_{HP} * EF_{E}$$ *Equation A17*

$$\Delta CO_2(i) = \Delta CO_{2,res}(i) + \Delta CO_{2,com}(i) - CO_{2,HP}(i)$$ *Equation A18*

Sensitivity analyses were conducted using an assumed COP of 4.00. The results are provided in a separate document.

A2.2. Heat Pump Coefficient of Performance

Foster, Love and Walker (2016) note that costs and COP of heat pumps exhibit a large range of values depending on the operating conditions and the temperature differential between heat source and heat sinks. The following table of cost and COP values were used in conducting sensitivity analyses in the authors' study of different scenarios for district heating in the UK. COP values for central HP were used in sensitivity analyses to test the impact of heat pump COP on energy use and GHG emission calculations. The results are reproduced in a separate document.

Table A1: COP data from Foster, Love and Walker (2016)

Category	**Unit**	**Low**	**Central**	**High**
COP - central HP	COP @ 10°C source, 70°C sink	1.5	2.21	3.6
COP - water-to-water building integrated HP	COP @ 10°C source, 45°C sink	3.86	4.53	5.31

The Heat Roadmap Europe (HRE) study developed a database on the status of DH using large-scale electric heat pumps in Europe. The survey examined the existing capacity of 149 large-scale electric heat pump units with thermal output capacity exceeding 1 MW, grouped by country, heating plant and in decreasing order of age. Data on each unit included information on heat sources, refrigerants used (in the case of district cooling systems), capacities, COP, input and output temperatures. Thermal output capacity, heat source, and input / output temperatures of heat pump units in the HRE database were compared with known parameters of the Xiantang proposed DH heat pump(s) to develop a secondary range of potential COP values. Only one HP system in Slovakia was comparable in terms of both heat source and input/ output temperatures (data shown below). As Foster, Love and Walker (2016) reported that input/ output temperatures were one of the most important controlling factors on COP, a range of COP values were generated from HPs with similar input/ output temperatures (shown below). The results are reproduced in a separate document.

Table A2: Summary HP data from David et al. (2017)

Country	Location	Source	Output Capacity (MW)	Source Temp. (C)	Supply Temp. (C)	COP
Slovakia	Umea	Waste heat	34.0	10-16	80	4.00
Czech Republic	Rye Kraftvarmevaerk	Geothermal aquifer	2.0	9	75	4.00
Denmark	Marstal	Heat storage (solar)	1.5	10-35	78	3.10
Denmark	Kakola (Turku)	Sewage water	21.0	10	78	3.30
France	Cherbourg (Divette)	Sea water	2.2	11	63	3.00
Netherlands	Horten	Sea water	2.4	5	68	3.00
Netherlands	Skoyen Vest (Oslo)	Sewage water (raw)	9.2	10	75	2.90
Norway	Fornebu (Oslo)	Sea water	6.9	5	75	3.06
Norway	Fornebu (Oslo)	Sea water	6.8	5	75	3.06
Norway	Sandvika (Oslo)	Sewage water	13.0	10	78	3.10
Norway	Trondheim	Sea water	1.2	11	55	4.03
Sweden	Lund	Sewage water	13.0	8-10	80	3.20
Sweden	Uppsala	Sewage water	36.0	9-18	70	3.20
Sweden	Schlossmatt (Munsingen)	Sewage water	1.1	10	62	3.44
Switzerland	Walche (Zurich)	River water	13.4	15	70	3.39
Switzerland	Lausanne	Lake water	4.5	7	65	4.80

Table A3: Summary statistics for HP data from David et al. (2017)

Mean	Mean +1 st.dv.	Mean -1 st.dv.	Max	Min
3.41	**3.94**	**2.89**	**4.80**	**2.90**

A3. Summary of Equation Changes

Equation 1

- number of buildings connected first rounded to the nearest whole number before calculating area connected (Apr 22, 2020)
- domain bounded to reflect 0% of buildings connected in 2020 (Apr 22, 2020)

Equation 2

- new equation added to calculate population within Steel Mill service area before calculating the number of residential buildings connected (Apr 21, 2020)

Equation 7 & 8

- summation included to indicate that total power capacity is the sum of power delivered by two HX/ HP systems in all scenarios (see District Heating spreadsheet, Exhibit G, cells C26-C27) (Apr 21, 2020)

Equation 13-16

- new equations added reflecting analogous approach to determine commercial serviceable area for each scenario (Apr 23, 2020)

Equation 21-24

- domain defined to only include situations where capacity for commercial service > 0 (Apr 21, 2020)
- excess capacity for residential multiplied by ratio of commercial serviceable area to residential serviceable area (rather than load index ratio) (Apr 23, 2020)
- A(res,B,HX) reflects a constant (total serviceable area) rather than a function of (i) (Apr 23, 2020)

Equation 25-28

- new equations added following procedure for calculating residential energy savings applied to commercial (Apr 21, 2020)

Equation 30-31

- formula for delta(P)res broken into two domains such that the lesser of area connected and serviceable area is used to calculate actual energy savings (Apr 21, 2020)
- note: calculation for commercial energy savings differs from calculation for residential energy savings by using the lesser of A(i)com,DH (commercial area connected) and A(i)com,B,HX (remaining space heating capacity for commercial after satisfying residential demand)

Equation 32-35

- power consumed by DH pump replaced with (power recovered by DH system) * (water pump efficiency) (Apr 21, 2020)
- domain limit added to equation 33 to prevent division by zero (Apr 21, 2020)

Equation 36-39

- formula for delta(P)res broken into two domains such that the lesser of area connected and serviceable area is used to calculate actual energy savings (Apr 21, 2020)

Equation 47-51, 53-56

- only marginal energy provided by HP above energy extracted by HX associated with energy cost (Apr 23, 2020)
- domain bounded to explicitly define area served as the lesser of area connected and total serviceable area (Apr 23, 2020)
- note: calculation for energy cost of HP for commercial service differs from calculation for residential service by using the lesser of A(i)com,DH (commercial area connected) and A(i)com,B,HX (remaining space heating capacity for commercial after satisfying residential demand) (Apr 23, 2020)

Equation 59-66

- formulas broken out for each scenario (Apr 23, 2020)