Explanatory Note on the Green Building 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 Green Building Strategy 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 policy-based actions for the promotion of green building standards in Yuhu and Yuetang Districts.

The baseline scenario represents a 'Business as Usual" (BAU) case where the composition of the buildings and all incentives for retrofits or green building construction 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 two project-based actions and five policy-based actions. These actions are:

Project-based modifications examined:

1. Green, low-carbon, resilient Xiangtan No. 1 Hospital. This includes IFC-EDGE certification, low-carbon equipment, hospital structural civil works, resilient rain garden/EbA facilities design.
2. Public building retrofitting for low-carbon demonstration. This includes IFC-EDGE certification, building renovation civil works, and procurement of low-carbon green products.

Policy-based modifications examined:

1. Enhancement of green building strategy through quantifiable (EDGE) green building certification
2. Action plan on passive buildings promotion
3. Implementation plan on enhancement of inclusive access to buildings
4. Implementation of a program to increase local capacity for EDGE certified green building
5. Design guidelines and standards on passive building and housing design

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

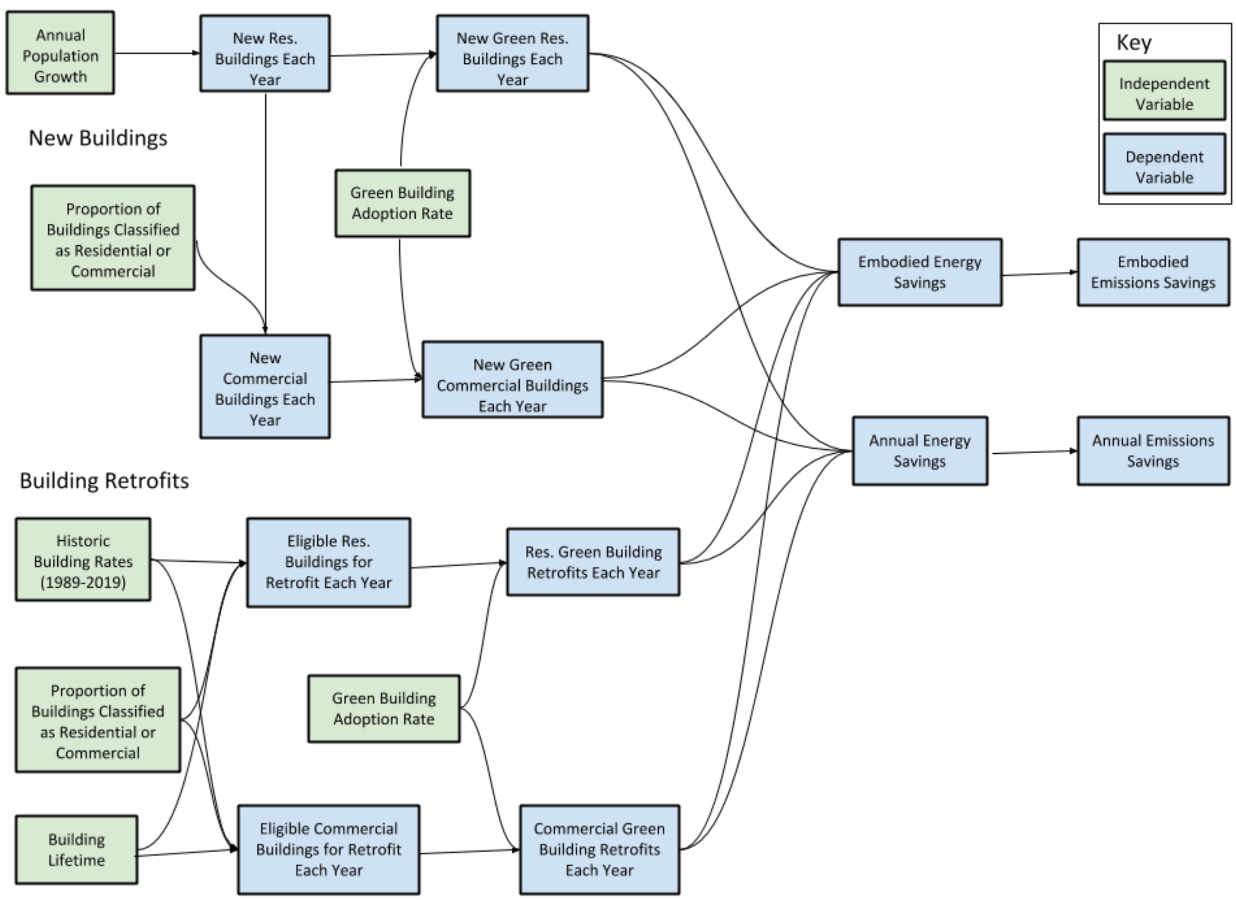
GHG emissions followed by a rapid decline. These are the two most extreme RCP scenarios; thus, movement from one to the other represents the most ambitious goal.

2. Assumptions

1. "Green" building standards encompass EDGE Certification and passive building standards.
2. "Commercial" and "public/ commercial" buildings include all non-residential buildings.
3. Green building policies will apply to all new and existing public/ commercial and residential buildings in YH and YT (see Appendix, Figure A1 and A2) built since 1989.
4. 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).
5. Green building adoption models assume initial (2019) adoption rates near 0% based on observation that only one building from the Xiangtan was found within databases of existing certifications (LEED, EDGE, 3 Star).
6. Starting the adoption of green building standards at 19% for retrofitted construction in 2017 reflects data from Changning District's public building sector. Building retrofit projects completed before 2022 are assumed to occur without influence of XT green building policy, while retrofit projects completed after 2022 are attributed to XT green building policy. This ignores the possibility of retrofit projects that would have occurred without additional incentives provided by XT green building policy. As of 2018, 44% of institutional, commercial, and industrial building owners surveyed in the 2018 Energy Efficiency Indicators survey expressed intent to pursue green building certification in the future, which may suggest the number of building owners pursuing retrofit projects in a BAU scenario is greater than zero (Johnson Controls 2018).
7. The national goal of 50% of new buildings certified as "green" in 2020 is presented for context and it is not plausible that the goal will be exceeded. We assume there will be a new national goal in the upcoming 14th 5-year plan.
8. Each year after 2019, a certain number of existing buildings reach the end of their expected lifetime and become prime candidates for retrofit. The number of eligible buildings is based on historic building rates 1989-2019 and average expected lifetime of urban buildings in China. Of these buildings, a certain percentage each year will be retrofitted based on a logistic growth model for adoption of green building practices and standards. All other existing buildings are assumed to undergo any modifications or upgrades necessary to continue operating at the same energy efficiency level.
9. Buildings built before 1989 are not considered for EDGE retrofit, due to uncertainties in the quality of older building stock and any impediments to sustainability upgrades that may exist. See Paradis (2016) for examples and further discussion of potential barriers to sustainability upgrades in older buildings.
10. Average annual energy savings for commercial and public buildings assume energy savings per unit floor area for both new and retrofitted public and commercial buildings will mirror annual energy savings calculated for the project-based component, Xiangtan public building retrofit for low-carbon demonstration.
11. Average annual energy savings for residential buildings assume energy savings per unit floor area for both new and retrofitted residential buildings will mirror annual energy savings calculated for the project-based component, EDGE Certified Hospital technical dormitory building.
12. Average reductions in embodied energy of building materials for new commercial/ public buildings are assumed to mirror average percentage reductions in embodied energy achieved or anticipated for EDGE Certified warehouse, office, retail, and education buildings in China in the EDGE project database as of April 2020.
13. Average reductions in embodied energy of building materials for new residential buildings are assumed to mirror average percentage reductions in embodied energy achieved or anticipated for EDGE Certified homes and hotels in China in the EDGE project database as of April 2020.
14. Average reductions in embodied energy of building materials for retrofitted commercial/ public buildings are assumed to mirror embodied energy reductions per unit floor area calculated for the project-based component, Xiangtan public building retrofit for low-carbon demonstration.
15. Average reductions in embodied energy of building materials for retrofitted residential buildings are assumed to mirror embodied energy reductions per unit floor area calculated for the project-based component, EDGE Certified Hospital technical dormitory building.

16. A constant emissions factor for the Central China Grid is applied to both electricity consumption and embodied energy in building materials. This assumption should be updated when better data on emission factors for embodied energy in building materials used in XT projects is available (see Section 4. User-Defined Inputs).
17. 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(s)	Data Source	Explanation
t_p *(year)*	2022	*Eq. 1*	XT PMO	*Year of Policy Implementation*
L (%)	100%	*Eq. 1*		*Maximum percentage of new or retrofitted buildings built to green standards* Logistic growth parameter reflecting maximum green building adoption rate.
k_{new} *(%)*	23%	*Eq. 1*	CBRE (2017)	*Logistic growth rate, green building adoption in new construction* Parameter chosen to reflect growth rate of ENERGY STAR and/or LEED certified space in the 30 largest U.S. office markets 2000-2017.

$t_{0,new}$ *(year)*	2039	*Eq. 1*	CBRE (2017)	*Green building adoption model midpoint year (new construction)* Parameter chosen to reflect growth rate of ENERGY STAR and/or LEED certified space in the 30 largest U.S. office markets 2000-2017.
$k_{retrofit}$*(%)*	9%	*Eq. 1*	Molinaroli (2017)	*Logistic growth rate, green building adoption rate (retrofits)* Parameter chosen to match the starting percentage of about 19% adoption rate in 2017, reflective of data from Changning District's public building sector.
$t_{0,retrofit}$ *(year)*	2033	*Eq. 1*		*Green building adoption model midpoint year (retrofits)* Parameter chosen to reflect gradual adoption over the lifetime of the loan.
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} *(%)*	33.50%	*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_{res} *(%)*	64%	*Eq. 3* *Eq. 8* *Eq. 9* *Eq. 10* *Eq. 11*	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.
ζ_{pph} *(persons/ household)*	3.10	*Eq. 2*	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.
$\zeta(i)_{hpb}$ *(households/ building)* *i=1990-1999*	56	*Eq. 2* *Eq. 8* *Eq. 10*	Gálvez and Cheshmehzangi (2015), p 6	*Residential units per building (1990-1999)* Starting in 1988, work unit-based housing systems were abolished and replaced by new affordable housing projects characterized by low-cost mass housing construction consisting of housing blocks of 56 mid-sized units each.
$\zeta(i)_{hpb}$ *(households/ building)* *i=2000-2045*	120	*Eq. 2* *Eq. 8* *Eq. 10*	Gálvez and Cheshmehzangi (2015), p 8	*Residential units per building (2000-2045)* 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 ("gated community" housing pattern). 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.

τ_j *(years)* *j=1989-1999*	30	*Eq. 6*	Hong et al. (2016), p 50	*Estimated lifetime of buildings built 1989-1999* Following assumptions for average lifetime of urban residential and commercial buildings in China 1980-1999.
τ_j *(years)* *j=2000-2009*	40	*Eq. 6*	Hong et al. (2016), p 50	*Estimated lifetime of buildings built 2000-2009* Following assumptions for average lifetime of urban residential and commercial buildings in China 2000-2019.
τ_j *(years)* *j=2010-2019*	40	*Eq. 6*	Hong et al. (2016), p 50	*Estimated lifetime of buildings built 2010-2019* Following assumptions for average lifetime of urban residential and commercial buildings in China 2000-2019.
τ_j *(years)* *j=2020-2029*	50	*Eq. 6*	Hong et al. (2016), p 50	*Estimated lifetime of buildings built 2020-2029* Following assumptions for average lifetime of urban residential and commercial buildings in China 2020-2050.
τ_j *(years)* *j=2030-2039*	50	*Eq. 6*	Hong et al. (2016), p 50	*Estimated lifetime of buildings built 2030-2039* Following assumptions for average lifetime of urban residential and commercial buildings in China 2020-2050.
τ_j *(years)* *j=2040-2045*	50	*Eq. 6*	Hong et al. (2016), p 50	*Estimated lifetime of buildings built 2040-2045* Following assumptions for average lifetime of urban residential and commercial buildings in China 2020-2050.
s_{res} *(%)*	34%	*Eq. 8*	IFC (2015)	*Average Reduction in Embodied Energy for new EDGE residential building compared to a typical residential building* Case study of an EDGE certified hotel in China used to estimate average percentage reduction in embodied energy of EDGE certified residential buildings relative to typical residential buildings.
s_{com}*(%)*	28%	*Eq. 9*	IFC (2017); IFC (2018)	*Average Reduction in Embodied Energy For new EDGE public/ commercial building compared to a typical public/ commercial building* Case studies of EDGE certified commercial buildings in China used to estimate average percentage reduction in embodied energy of EDGE certified commercial buildings relative to typical commercial buildings.
$E_{\varepsilon,res}$*(GJ/ m²)*	6.60	*Eq. 8*	Azari and Abbasabadi (2018)	*Typical Average Embodied Energy for new residential building* Average values for life cycle embodied energy of initial construction for residential building types reported by Azari and Abbasabadi (2018).
$E_{\varepsilon,com}$*(GJ/ m²)*	9.58	*Eq. 9*	Azari and Abbasabadi (2018)	*Typical Average Embodied Energy for new public/ commercial building* Average values for life cycle embodied energy of initial construction for commercial building types reported by Azari and Abbasabadi (2018).

$\delta E_{\varepsilon,res}(GJ/m^2)$	1.73	*Eq. 8*	Shaofang Li (2020)	*Average embodied energy reduction per square meter for green retrofitted residential building* Based on average embodied energy reduction estimated for the project-based component, EDGE certified hospital retrofit, technical dormitory building
$\delta E_{\varepsilon,com}(GJ/m^2)$	0.73	*Eq. 9*	Shaofang Li (2020)	*Average embodied energy reduction per square meter for green retrofitted commercial building* Based on average embodied energy reduction estimated for the project-based component, Xiangtan government building retrofit
ζ_{aph} *(m^2/ household)*	138.88	*Eq. 8* *Eq. 10*	XT PMO	*Household living space, 2019* ADB Survey of households Aug 2019 asked (Q 22) "What is the status of your home? ____m2" 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. 9* *Eq. 11*	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.
EF_M *(tCO_2e/ GJ)*	0.13	*Eq. 8* *Eq. 9*	XT PMO	*Emission factor for building materials* Conversion from GJ to kWh to tCO2e assuming an emission factor equal to the emission factor for electricity in XT.
δP_{res} *(kWh/ m^2)*	178.71	*Eq. 10*	Shaofang Li (2020)	*Annual energy savings per square meter for green residential buildings* Assumed to mirror energy savings per square meter calculated for the project-based component, EDGE Certified Hospital technical dormitory building
δP_{com} *(kWh/ m^2)*	58.86	*Eq. 11*	Shaofang Li (2020)	*Annual energy savings per square meter for green commercial buildings* Assumed to mirror energy savings per square meter calculated for the project-based component, Xiangtan public building retrofit for low-carbon demonstration.
EF_E *(tCO_2e/ kWh)*	0.000462	*Eq. 12*	ADB	*Emission factor for electricity use* From Central China Grid.

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 "Green Building Emissions Calculations - Xiangtan ADB Output 3, 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. Green Building Adoption Rates for New and Retrofitted Buildings

Adoption of green building standards in new construction 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, and growth in commercial building space is extrapolated from residential building growth based on current proportions of each building type in XT building stock. Green building adoption rates are applied to building projections to estimate the number of new buildings built to green building standards each year. Each year after 2019, a certain number of existing buildings reach the end of their expected lifetime and become prime candidates for retrofit. The number of eligible buildings is based on historic building rates 1989-2019 and average expected lifetime of urban buildings in China. A similar model is applied to eligible buildings each year to estimate the percentage of eligible buildings retrofitted to green building standards each year.

$$y(i) = \frac{L}{1+exp(k*(t_0-t_i))} \qquad for\ i \geq t_P,\ 0\ otherwise \qquad \textit{Equation 1}$$

Where:

$y(i) = Percentage\ of\ new/\ retrofitted\ buildings\ built\ to\ green\ building\ standards\ in\ year\ i\ (\%)$
$L = maximum\ percentage\ (\%)$
$k = logistic\ growth\ rate\ (\%)$
$t_0 = midpoint\ year$
$t_i = year\ i$
$t_p = year\ of\ policy\ implementation$

$$B(i)_{res} = r * p_{YH+YT} * \frac{1}{\zeta_{pph}} * \frac{1}{\zeta(i)_{hpb}} \qquad \textit{Equation 2}$$

$$B(i)_{com} = B(i)_{res} * (\frac{1}{p_{res}} - 1) \qquad \textit{Equation 3}$$

$$B(i) = B(i)_{res} + B(i)_{com} \qquad \textit{Equation 4}$$

$$B(i)_{green} = y(i)_{new} * B(i) \qquad \textit{Equation 5}$$

$$\beta(i) = B(i - \tau_j) \qquad \textit{Equation 6}$$

$$\beta(i)_{green} = y(i)_{retrofit} * \beta(i) \qquad \textit{Equation 7}$$

Where:

$B(i) = total\ number\ of\ new\ buildings\ built\ in\ year\ i$
$B(i)_{res} = total\ number\ of\ new\ residential\ buildings\ built\ in\ year\ i$
$B(i)_{com} = total\ number\ of\ new\ commercial\ buildings\ built\ in\ year\ i$
$r = population\ growth\ rate\ (persons/year)$
$p_{YH+YT} = percentage\ of\ Xiangtan\ residents\ living\ in\ YH\ and\ YT\ (\%)$
$p_{res} = percentage\ of\ building\ stock\ classified\ as\ residential\ (\%)$
$\zeta_{pph} = average\ population\ per\ household\ (persons/household)$
$\zeta(i)_{hbp} = average\ number\ of\ households\ per\ residential\ building\ in\ year\ i\ (households/building)$
$B(i)_{green} = number\ of\ new\ buildings\ built\ to\ green\ building\ standards\ in\ year\ i$
$\beta(i) = number\ of\ buildings\ eligible\ for\ retrofit\ in\ year\ i$
$\tau_j = average\ lifetime\ of\ buildings\ built\ in\ year\ j\ (years),\ where\ i = j + \tau_j$
$\beta(i)_{green} = number\ of\ buildings\ retrofitted\ to\ green\ building\ standards\ in\ year\ i$

5.2. Embodied CO_2 Emissions Savings

Average reductions in embodied energy of building materials for new commercial/ public buildings are assumed to mirror average percentage reductions in embodied energy achieved or anticipated for EDGE Certified warehouse, office, retail, and education buildings in China, and average reductions in embodied energy for residential buildings are assumed to mirror average percentage reductions achieved by EDGE Certified homes and hotels in China. Average reductions in embodied energy per unit floor area are calculated as this percentage multiplied by the

average embodied energy per unit floor area of public and commercial buildings or residential buildings reported by Azari and Abbasabadi (2018). Summary data are included in the Appendix.

Average reductions in embodied energy of building materials for retrofitted commercial/ public buildings are assumed to mirror embodied energy reductions per unit floor area calculated for the project-based component, Xiangtan public building retrofit for low-carbon demonstration. Average reductions in embodied energy of building materials for retrofitted residential buildings are assumed to mirror embodied energy reductions per unit floor area calculated for the project-based component, EDGE Certified Hospital technical dormitory building (summary data included in the Appendix). Embodied energy is converted to emissions using the emissions factor for electricity in China, but this emissions factor can be updated based on emissions factors for building materials used in the EDGE software. Embodied emission reductions are only attributed to the year in which the construction or retrofit project is expected to finish.

$$\Delta CO_{2,\varepsilon,\,res}(i) = (B(i)_{green} * s_{res} * E_{\varepsilon,res} * \zeta(i)_{hpb} + \beta(i)_{green} * \delta E_{\varepsilon,res} * \zeta(i-\tau_j)_{hpb}) * p_{res} * EF_M * \zeta_{aph} \quad \text{Equation 8}$$

$$\Delta CO_{2,\varepsilon,\,com}(i) = (B(i)_{green} * s_{com} * E_{\varepsilon,com} + \beta(i)_{green} * \delta E_{\varepsilon,com}) * (1-p_{res}) * EF_M * \zeta_{apb} \quad \text{Equation 9}$$

Where:

$\Delta CO_{2,\varepsilon,\,res}(i)$ = *embodied* CO_2 *emission reduction from residential construction in year i* (tCO_2e)
$\Delta CO_{2,\varepsilon,\,com}(i)$ = *embodied* CO_2 *emission reduction from commercial construction in year i* (tCO_2e)
s_{res} = *average reduction in embodied energy for new EDGE Certified residential buildings* (%)
s_{com} = *average reduction in embodied energy for new EDGE Certified commercial buildings* (%)
$E_{\varepsilon,res}$ = *average embodied energy per square meter for typical new residential building* (GJ/m^2)
$E_{\varepsilon,com}$ = *average embodied energy per square meter for typical new commercial building* (GJ/m^2)
$\delta E_{\varepsilon,res}$ = *average embodied energy reduction per* m^2 *for green retrofitted residential building* (GJ/m^2)
$\delta E_{\varepsilon,com}$ = *average embodied energy reduction per* m^2 *for green retrofitted commercial building* (GJ/m^2)
EF_M = *emission factor for building materials* (tCO_2e/GJ)
ζ_{aph} = *average living space area per household* ($m^2/household$)
ζ_{apb} = *average floor area per commercial building* ($m^2/building$)

5.3. Annual Energy and Emission Savings for New and Retrofitted Buildings

Average annual energy savings for commercial and public buildings assume energy savings per unit floor area for both new and retrofitted public and commercial buildings will mirror annual energy savings calculated for the project-based component, Xiangtan public building retrofit for low-carbon demonstration. Average annual energy savings for residential buildings assume energy savings per unit floor area for both new and retrofitted residential buildings will mirror annual energy savings calculated for the project-based component, EDGE Certified Hospital technical dormitory building (summary data included in the Appendix).

$$\Delta P(i)_{res} = (\sum_{2020}^{i} B(i)_{green} * \zeta(i)_{hpb} + \sum_{2020}^{i} \beta(i)_{green} * \zeta(i-\tau_j)_{hpb}) * p_{res} * \delta P_{res} * \zeta_{aph} \quad \text{Equation 10}$$

$$\Delta P(i)_{com} = (\sum_{2020}^{i} B(i)_{green} + \sum_{2020}^{i} \beta(i)_{green}) * (1-p_{res}) * \delta P_{com} * \zeta_{apb} \quad \text{Equation 11}$$

$$\Delta CO_2(i) = (\Delta P(i)_{res} + \Delta P(i)_{com}) * EF_E + \Delta CO_{2,\varepsilon,\,res}(i) + \Delta CO_{2,\varepsilon,\,com}(i) \quad \text{Equation 12}$$

Where:

$\Delta P(i)_{res}$ = *annual energy savings in year i from all green residential buildings* (kWh)
$\Delta P(i)_{com}$ = *annual energy savings in year i from all green commercial buildings* (kWh)
δP_{res} = *annual energy savings per square meter for green residential buildings* (kWh/m^2)
δP_{com} = *annual energy savings per square meter for green commercial buildings* (kWh/m^2)
$\Delta CO_2(i)$ = *total annual emission reductions from green building policy in year i* (tCO_2e)
EF_E = *emission factor for electricity* (tCO_2e/kWh)

6. Key References

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Appendix

A1. ABBREVIATIONS AND ACRONYMS

ADB	Asian Development Bank
CO_2	Carbon Dioxide
tCO_2e	Tonnes of Carbon Dioxide Equivalents
EF	Emissions Factor
GHG	Greenhouse Gas
BAU	Business As Usual
XT	Xiangtan
XTMG	Xiangtan Municipal Government
XT PMO	Xiangtan Program Management Office
YT	Yuetang District
YH	Yuhu District
GJ	Gigajoule
EDGE	Excellence in Design for Energy Efficiencies
MW	Megawatt
MWh	Megawatt-hour
kW	Kilowatt
kWh	Kilowatt-hour
^{o}C	Degrees Celsius

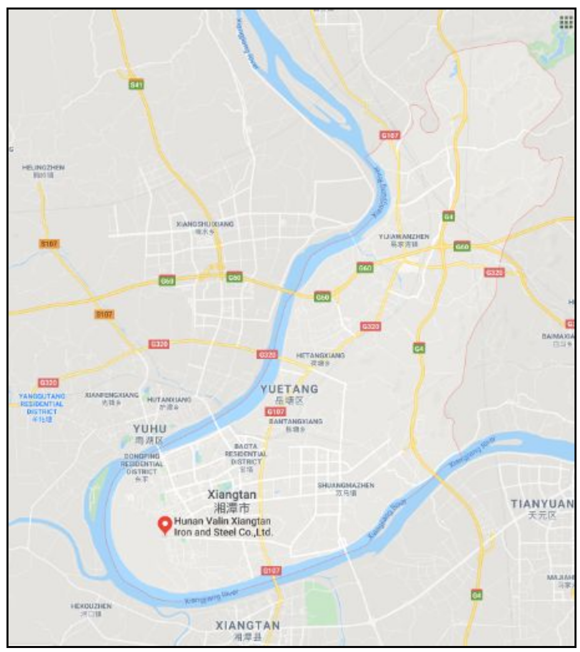

Figure A1: Yuhu District (outlined in red)

Figure A2: Yuetang District (outlined in purple)

Table A1. Policy-Based Interventions

Code	Interventions (Tranche 1 Policies)	Details and Effects on Low-Carbon Building Design and Adoption
03-Tr1a	Xiangtan notice on the enhancement of green building strategy through quantifiable (EDGE) green building certification	Removing the knowledge barriers to EDGE building design will increase the number of building owners choosing EDGE design or retrofitting building to EDGE design standards.
		Tenants' willingness to pay higher rents for EDGE certified buildings will generate an increase in developers choosing to pursue EDGE certification through new buildings or retrofits.
		Increase in EDGE certified buildings will generate a further increase in certifications as developers work to stay cutting-edge.
		Increased awareness on the benefits of EDGE green building certification will lead to increased demand and uptake.
		Promotion of a globally-known standard, such as EDGE, that investors are familiar with can increase the likelihood of investment in EDGE projects.
		Governmental adoption of EDGE certified buildings will lead to increased demand on developers to create EDGE certified buildings.
03-Tr1e	Xiangtan action plan on passive buildings promotion	Increased awareness on the benefits of passive building design will lead to increased demand and uptake.
		Removing the knowledge barriers to passive building design will increase the number of building owners choosing passive design or retrofitting buildings to passive design standards.
		Increased number of passive buildings constructed will lead to an increase in local specialists and local materials providers.
		Increased local specialists and providers of passive building materials will lead to a decrease in cost of passive design.
		Governmental promotion of passive buildings will lead to increased share of municipal buildings that meet passive building standards.
		Governmental promotion of passive buildings will lead to increased demand on developers to adopt passive building design standards.

Interventions (Tranche 2 Policies)		
03-Tr2a	Xiangtan implements a program to increase local capacity for EDGE certified green building.	Increased local capacity will increase knowledge about green building standards, in turn increasing low-carbon building design adoption.
		Increased local capacity will reduce technical barriers to green building construction, in turn increasing low-carbon building design adoption.
		Demonstrated ROI of green certified green buildings will increase investor adoption of green building standards.
		Training planners, building inspectors and other government staff on how to qualify green building design will lead to more green building project starts.
		Increased capacity can reduce permitting times for green building projects will incentivize green buildings over the slower permitting process for standard projects.
03-Tr2f	Xiangtan design guidelines and standards on passive building and housing designs	Having official design standards will increase developer and consumer confidence and increase passive building starts and renovations.
		Comprehensive guidelines, including information on the passive building premium will increase investor/developer confidence in passive buildings as an investment.
		Explicit written guidelines lowers knowledge barriers to passive building design which increases the adoption within the community.

A2. Summary Data

A2.1. Embodied CO_2 of Building Materials for New Construction

The following data, reproduced from Azari and Abbasabadi (2018), Table 1, are used in calculating embodied energy per unit floor area of new construction for both residential and commercial buildings. Only values for initial construction are included to reflect annual emissions savings associated with buildings constructed each year.

Table A2. Literature values for life cycle embodied energy of different building types

Primary Author	Building Type	Life cycle embodied energy lower value (GJ/m^2)	Life cycle embodied energy average value (GJ/m^2)	Life cycle embodied energy upper value (GJ/m^2)
Adalberth	Residential	-	3.7	-
	Residential	-	3.5	-
	Residential	-	2.9	-
Ding	Residential	3.6	-	8.78
	Commercial	3.4	-	19
	High-school (Public)	2.94	-	12.96
Aktas and Bilec	Residential (conventional)	1.7	-	7.3
	Residential (low-energy)	4.3	-	7.7
Dixit	Residential (brick)	0.9	-	16.3
	Residential (concrete)	0.9	-	23.1
	Residential (steel)	0.9	-	19.2
	Residential (wood)	0.9	-	6.6
Average	**Residential**	**-**	**6.60**	-
	Commercial/ Public	**-**	**9.58**	-

A2.2. EDGE Certified Building Retrofit

Energy savings per unit floor area for EDGE certified commercial buildings and embodied energy of building materials per unit floor area for EDGE certified commercial building retrofit projects are extrapolated to all commercial buildings from estimates for the project-based component, Xiangtan Government Building Retrofit (Asia Pacific Low-Carbon Development Training Center).

Table A3. Estimated energy savings per unit floor area for Xiangtan Government Building Retrofit (Shaofang Li 2020).

Parameter	Original Design	EDGE Design	Net Reduction
Annual Energy Use (MWh)	1,597.05	1,223.42	373.63
Embodied Energy in	-	-	4,606.54

Materials (GJ)			
Annual Water Use (m^3)	10,505.40	7,884.00	2,621.40
Total CO_2 Emissions (tCO_2e)	-	-	566.23
Annual Utility Cost (CNY)	1,120,934.40	858,273.12	262,661.28
Incremental Cost	1,753,817.69 CNY	-	251,371.32 USD
Payback Period (years)	6.68		
Total Floor Area (m^2)	6,347.80		
Energy Savings per m^2 (kWh/m^2)	58.86		
Embodied Energy Savings per m^2 (GJ/m^2)	0.73		

A2.3. EDGE Certified Hospital Retrofit - Technical Dormitory Building

Energy savings per unit floor area for EDGE certified residential buildings and embodied energy of building materials per unit floor area for EDGE certified residential building retrofit projects are extrapolated to all residential buildings from estimates for the project-based component, green, low-carbon, resilient Xiangtan First Traditional Chinese Medicine Hospital, technical dormitory building.

Table A4. Estimated energy savings per unit floor area for Xiangtan First Traditional Chinese Medicine Hospital, technical dormitory building (Shaofang Li 2020).

Parameter	Original Design	EDGE Design	Net Reduction
Annual Energy Use (MWh)	2,758	2,002	757
Embodied Energy in Materials (GJ)	27,348	20,030	7,318
Annual Water Use (m^3)	16,191	12,372	3,819
Total CO_2 Emissions (tCO_2e)	-	-	533
Annual Utility Cost (CNY)	2,775,763	1,976,249.76	799,514
Incremental Cost	2,930,852 (CNY)	-	420,073 USD
Payback Period (years)	3.67		
Total Floor Area (m^2)	4,234		
Energy Savings per m^2 (kWh/m^2)	178.71		
Embodied Energy Savings per m^2 (GJ/m^2)	1.73		

A3. Summary of Equation Changes

Equation 1

- domain bounded to only impact adoption rate after year of policy implementation (Apr 21, 2020)

Equation 2-4

- B(i)new broken into components and households per building made variable with time (Apr 21, 2020)

Equation 6

- new equation defining buildings eligible for retrofit based on building lifespan (Apr 21, 2020)

Equation 8-9

- embodied emissions for both new and retrofitted buildings combined, new and retrofitted green buildings redefined using total new/ retrofitted green buildings and p(res). Households per building made time-dependent (Apr 21, 2020)

Equation 10

- new and retrofitted green buildings redefined using total new/ retrofitted green buildings and p(res). Households per building made time-dependent (Apr 21, 2020)

Equation 12

- all emission reductions from policy-based component combined (Apr 21, 2020)