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ABSTRACT

Building energy accounts for about 30% of China's total annual energy consumption. China's fast urbanization makes building energy efficiency a crucial economic issue; however, only limited studies have been done that examined how to design and select suitable building energy technologies in different regions of China. This paper reports the results of a regional study of Chinese commercial and residential building energy use for optimal building energy performance. One retail and one multi-family residential prototype building are selected for this study, and their energy performance is analyzed in major Chinese cities and climate zones. To optimize each building's performance, several distributed energy resources such as combined heat and power (CHP), photovoltaics (PV), and battery storage, are considered for the selected building. Other data, for example solar radiation, electricity tariff, technology costs, and government financial incentives, are also collected for the study. The optimal building energy performance is calculated using the Distributed Energy Resources Customer Adoption Model (DER-CAM) which minimizes building energy cost or CO_2 emissions, or a combination. The trade-off between these objectives is also analyzed for the case buildings. Finally, this paper discusses suitable building energy technologies for different building types in different Chinese climate regions.

Keyword: Building Modeling and Simulation, Electricity, Efficiency Potential & Market Analysis, Distributed Generation, Combined Heat and Power (CHP), DER-CAM

Introduction

China has surpassed the U.S. as the world's largest energy consumer and CO_2 emitter. Buildings in China and the U.S. consumed about 40% and 25% of the primary energy in 2010 respectively; therefore, improving building efficiency in order to reduce energy demand has become one of the most pressing goals in both countries.

The purpose of this study is to investigate the applicability of a variety of distributed energy resources (DER) technologies in different climatic regions of China based on energy economic optimizations. Technologies assessed include photovoltaics (PV), solar thermal, gas turbines, microturbines, fuel cells, combined heat and power (CHP), and electrical storage in batteries. The goal is to help China understand what DER systems configurations are economically suitable under the influence of financial and technological factors, and the greenhouse gas (GHG) emission reduction potential for DER technologies.

Currently, the common practice of evaluating individual technology's potential for building energy efficiency and on-site generation is ineffective and almost never finds the global optimum. To tackle climate change, government policies often promote clean technologies such as PV or fuel cells and provide incentives for their adoption irrespective of how the technologies are applied. In both China and the U.S., the current strategy for promoting ultra low energy buildings relies heavily on dispersed renewable technologies combined with (by current standards) extreme efficiency measures. The cost effectiveness and energy saving potential from these technologies are highly sensitive to building energy services requirements, usage patterns, tariffs, and incentives. To holistically achieve the most cost or carbon effective building energy efficiency and on-site generation combination, multiple technology options and their operating schedules need to be evaluated and optimized simultaneously in order to choose the best technology combination for a particular building.

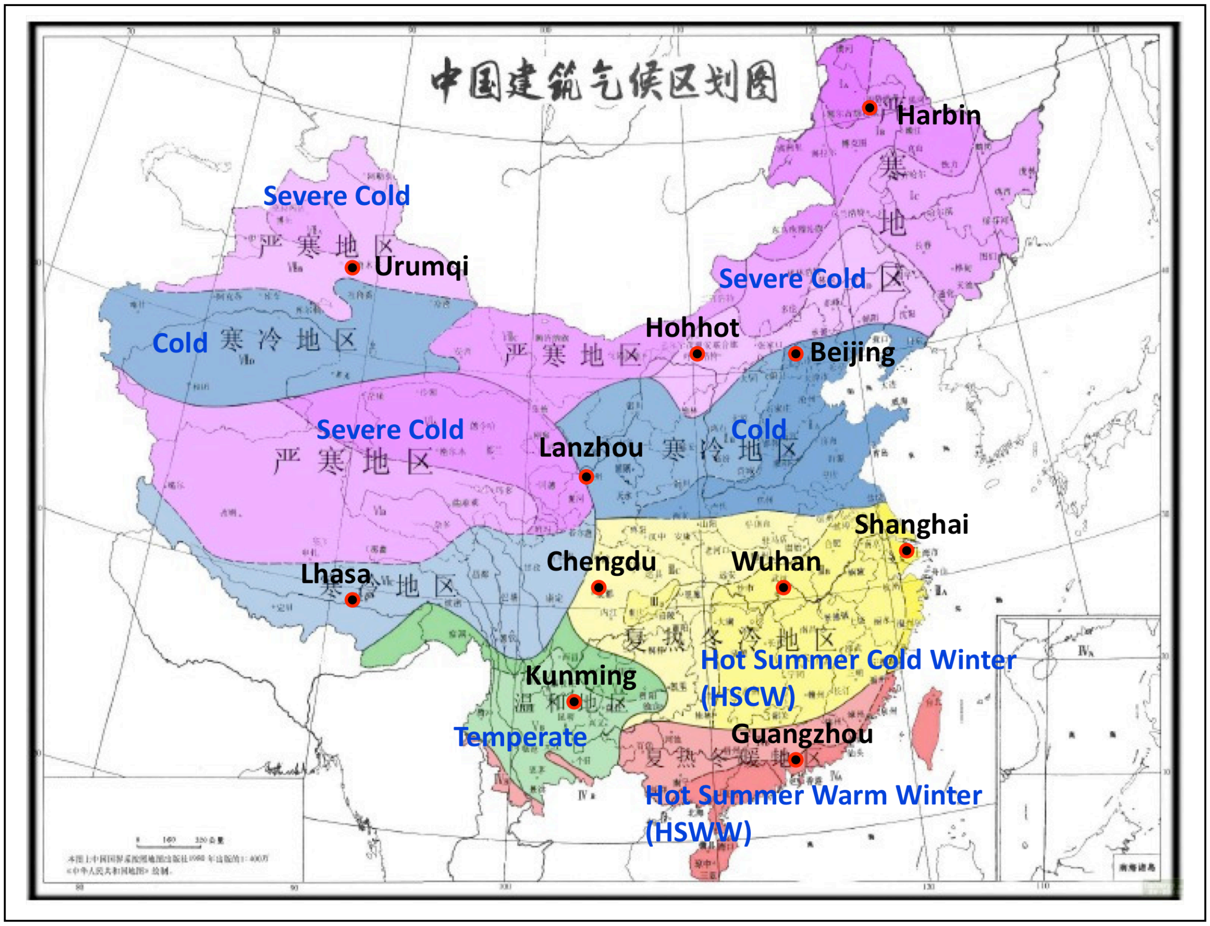
Methodologies

An optimization model, the Distributed Energy Resources Customer Adoption Model (DER-CAM) has been used in this study. DER-CAM has been in development by Lawrence Berkeley National Lab (LBNL) for over 10 years, and has been widely used to assess DER alternatives, to find optimal results, and for energy economic assessments. DER-CAM takes into account building or equipment operating constraints and finds the optimal supply technology combination and operating schedules. It can solve the entire building energy system holistically, simultaneously, and in a technology-neutral manner; that is, such that the cost, energy use, carbon, other metric, or combination of metrics is minimized, while all technology opportunities for service provision are equally considered and equitably traded off against each other (LBNL, 2012).

In this study, 11 representative Chinese cities – Harbin, Urumqi, Hohhot, Lanzhou, Beijing, Lhasa, Shanghai, Wuhan, Chengdu, Guangzhou, and Kunming are selected for DER system analysis. The selected cities are shown in the building climate zone map in Figure 1. The selection of those cities is based on the following factors:

- Climate zones and building energy loads
- Solar radiation profiles for PV assessment
- Electricity tariff
- Natural gas tariff
- Technology costs and financial considerations (such as interests rate, policy incentives etc.)

Figure 1 China's Building Climate Zone Map and Selected Cities

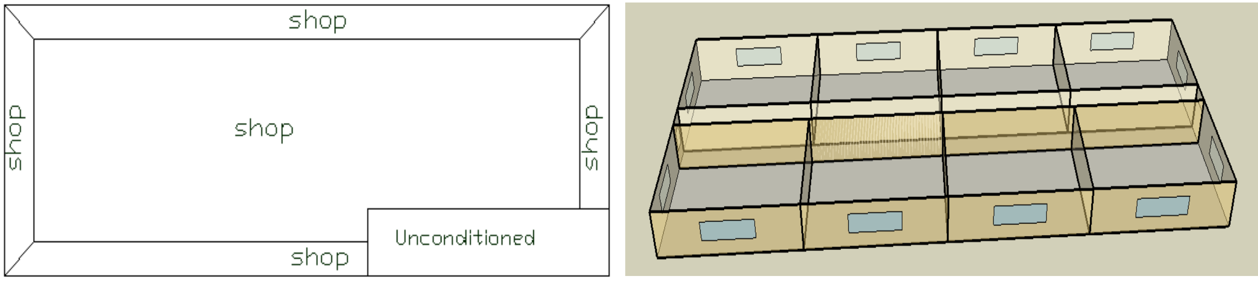


The distributed energy system modeling requires inputs such as building's energy load profile, city's solar radiation data, electricity and natural gas tariffs, and the performance and cost of the technologies. The methodology and key assumption of the key inputs are shown below.

Building type selection

In order to understand building energy performance in different climate zones, two Chinese prototype buildings are modeled. The commercial building is a 7-floor shopping center with 2 basement floors. The residential building is a 10-floor high-rise multi-family apartment (NREL, 2011; Field K., 2010). The floor plans of the prototype buildings are shown in Figure 2. The retail building prototype is developed by on-site survey and literature review and modeled in compliance with China's commercial building energy efficiency standard GB50189-2005 (Hong, 2009; MoHURD, 2005). The residential prototype building is developed based on U.S. DOE multi-family apartment prototype building, as well as Chinese studies in compliance with China's residential building energy efficiency standards (MoHURD, 2010; MoHURD, 2010; MoHURD, 2003). The prototype building characteristics are shown in Table 1 for Shanghai climate zone. Buildings in other climate zones are modeled with the similar internal load and lighting density, while building envelope parameters and HVAC operation schedules are determined based on Chinese commercial and residential building codes.

Figure 2 Prototype Buildings Floor Plans



Retail building floor plan Residential building floor plan

Table 1 Prototype Building Characteristics for Shanghai Climate Zone

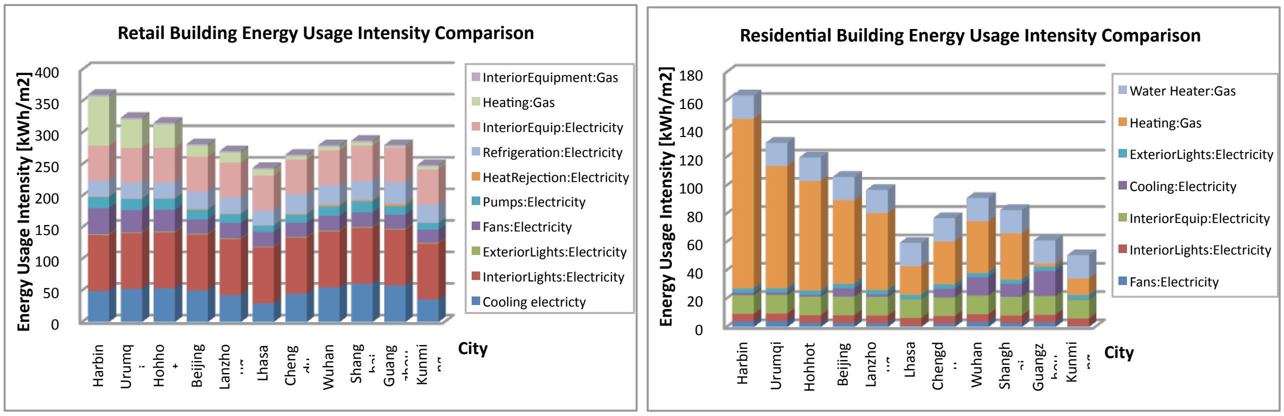
	Retail Building	Residential Building
Floors	7 floors above grade, 2 floors underground (B: retail, SB: parking) ; 4000 m2/floor	10 floors above grade, 783.6 m2/floor
Building Envelope	Ext-Wall: U = 1.0 W/m2•K	Ext-Wall: U = 1.0 W/m2•K
	Roof: U = 0.7 W/m2•K	Roof: U = 0.7 W/m2•K
Fenestration	Window to wall ratio (WWR) = 0.2	Window to wall ratio = 0.2
	Window: U = 4.7 W/m2•K	Window: U = 4.0 W/m2•K, SHGC = 0.4
	Shading: No	Shading: No
Lighting	Retail area: 20 W/m2	Apartment: 1.9 W/m2
	Parking: 2.4 W/m2	Office: 10 W/m2
Internal Loads	Max Occupancy: 3m2/person	Max Apt Occupancy: 2 persons/apt
	Equipment intensity: 13W/m2	Apt Equipment intensity: 2.3 W/m2
Infiltration	1 ACH	1.2 ACH
External Loads	Elevator and lift power: 4% of total electricity consumption	Elevator motor capacity: 15 kW
	Exterior Lighting: 2.2W per façade area (17:00-23:00)	Exterior Lighting: 1 W per façade area (17:00-23:00)
Operation Schedule	10:00-22:00	24/7
HVAC air sys	Constant Air Volume (CAV)	Room AC and DX coils, cooling COP = 3.1
	OA supply rate: 20m3/(h.person)	OA supply rate: 20m3/(h.person)
Cooling and heating source	Water Cooled Centrifugal Chillers (COP = 5.2)	
	Gas Boilers, efficiency = 0.8	
Pumps	Constant volume	

Cooling Tower	Constant speed fan	
Room temperature set point	Cooling: 25℃ ; Heating: 18℃	Cooling: 26℃ ; Heating: 18℃
Supply Air Temperature	Cooling: 17℃; Heating: 28℃	
HVAC operation seasons	Summer season: 4/1 -- 10/31	Summer season: 6/15 -- 10/1
	Winter season: 1/1 -- 3/31, 11/1 -- 12/31	Winter season: 1/1 -- 3/1, 11/15 -- 12/31

Building loads

In order to estimate the economic performance of DER technologies in China, it is important to understand the buildings' energy load profiles. The annual energy performance of the commercial and residential prototype buildings discussed in the previous section is simulated in EnergyPlus (DOE, 2011). The energy usage intensity is shown as site energy in Figure 3.

Figure 3 Commercial and Residential Building Site Energy Usage Intensity in China



The retail prototype building is an internal load dominated model in which lighting, internal equipment, and cooling consumes the majority of building's energy. The large internal load also makes the building use more energy on cooling than heating in most climate zones in China, and thus less sensitive to climatic impacts. In contrast, the residential prototype building's internal load is much smaller than the retail building, and thus the residential building is more sensitive to climate.

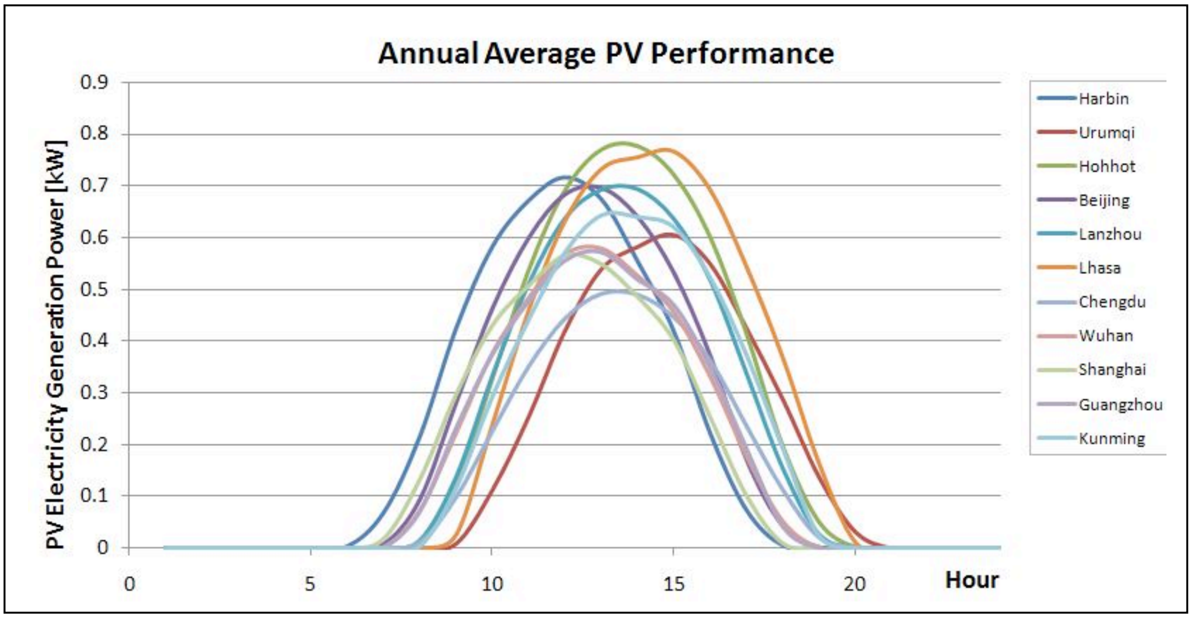
In both prototype cases, buildings in Kunming (Temperate climate zone) have the best energy performance. Buildings in Lhasa (Cold climate zone) uses less energy compared with buildings in other Cold climate regions, mainly because of its high altitude and ample solar radiation.

PV System Performance in Chinese Cities

To evaluate solar radiation and its impact on PV systems, PVWatts (NREL, 2011) data are used. Figure 4 shows crystalline silicon PV system electricity power performance in selected Chinese cities. The data are developed based on PV system AC rating of 1kW, DC to AC conversion rate of 0.77 (this gives DC rating of approximately 1.3kW, and the PV system approximate area of 11.4 m^2), and south facing fixed tilt angle panel installation. The data are developed by averaging PV system hourly AC output power on an annual basis.

It is found that the PV system performance in China vary from one region to another. And because there is only a single time zone in China, the PV peak electricity production time also differs across regions.

Figure 4 Chinese Cities' PV System Performance



Tariff

Electricity tariff (summer season) and natural gas tariff are shown in

Figure 5 and Figure 7. Most cities have summer and winter season rates, and cities with hydropower also have drought season, rainy season, and intermediate season rates. On a daily basis, most cities, except Hohhot and Lhasa, have peak, off-peak and intermediate rates for commercial buildings. For residential buildings, a flat tariff is most common, though some cities have optional time differentiated rates for consumers. Commercial natural gas tariff is slightly higher than residential in the same city. Generally, cities (except Kunming and Lhasa) in Western and Central China have relatively lower natural gas rates compared with cities in Eastern China.

Figure 5 Summer Electricity Tariff in Chinese Cities

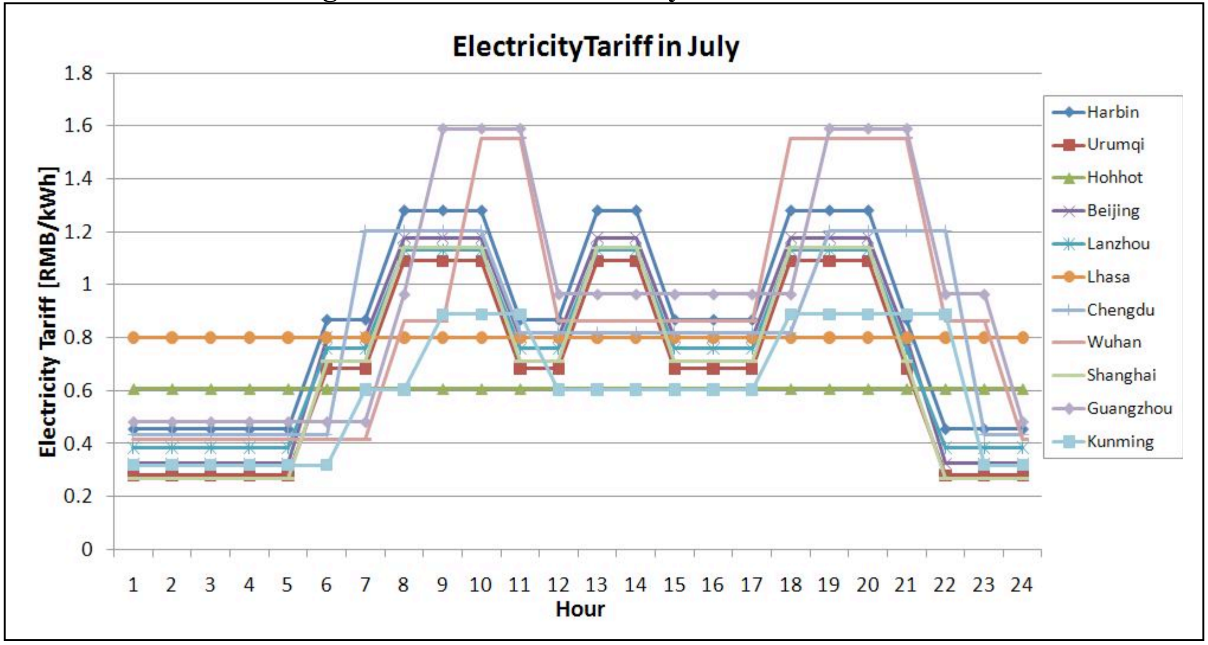
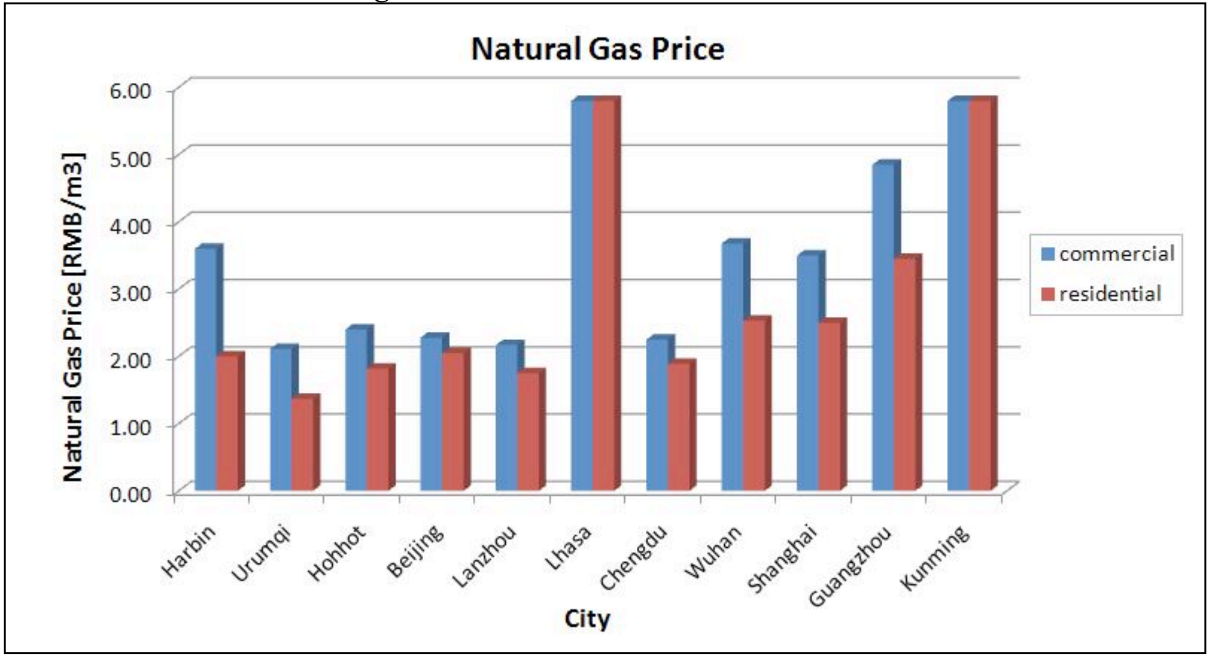


Figure 7 Natural Gas Tariff in Chinese Cities



Cost and technologies performance

Other important factors that will determine which technologies are suitable in different cities are costs and technologies performance. In this study, we have taken into account government incentives and estimated the technology costs in the current Chinese market. The cost data are shown in Table 2, and the cost is given in units of USD/kW or USD/kWh[1]. Particularly, for technologies such as PV, and electricity storage devices, the table shows the final user cost after 50% government cost sharing or subsidy.

Table 2 DER Technologies Cost Data in China (USD)

Technologies	**Fixed Cost**	**Variable Cost**	**Lifetime [years]**	**Fixed Maintenance ratio**[2]
Electricity Storage	0	100	6	0.0
Heat Storage	10,000	50	17	0.0
Flow Battery Energy	0	110	10	0.1
Flow Battery Power	0	1,060	10	0.0
Absorption Chiller	20,000	127	15	0.1
Abs. Refrigeration	20,000	127	15	0.1
PV	0	1,615	20	0.3
Solar Thermal	1,000	400	15	0.1

To estimate DER technologies' impact on GHG emission reduction, Table 3 shows the main grid systems in China and their marginal CO_2 emission factors[3] (NDRC, 2011). Since China's electricity is mainly generated from coal, the emission factors are generally higher than those in U.S. and other developed countries.

Table 3 China Macro-grid CO_2 Marginal Emission Factor

Region	**CO_2 marginal emission factor [tCO_2/MWh]**
North Grid	0.9803
Northeast Grid	1.0852
East Grid	0.8367
Central Grid	1.0297
Northwest Grid	1.0001
South Grid	0.9489

Results

Figure 8 illustrates the commercial building energy cost optimization results and its CO_2 abatement potential. Table 4 shows the selected DER technologies for the optimal energy cost solution outputted by DER-CAM. The result shows the optimal cost solution for commercial building when considering technology investment cost, energy consumption cost, energy

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[1] This study takes currency conversion rate of 6.5 RMB to 1 USD.

[2] Fixed Maintenance ratio is the cost ratio to fixed capital cost

[3] The marginal emission factor is calculated based on fossil fuel electricity generation. Research in this area is on-going; in the future, electricity generated by hydro, nuclear, and other renewable technologies will be incorporated into the power generation mix and contribute to the overall electricity emission factor.

conversion performance and renewable energy harvest. For each city, there is baseline case (or called "do-nothing" case), where electricity is purchased from macro-grid, and buildings use electricity for cooling and natural gas space heating. Because of large internal heat load in the retail building, electricity consumption for cooling takes the majority of building HVAC energy and its end use energy does not vary much from one city to another. Thus, climate difference is not a major consideration in this case if compared with factors such as energy tariff and incentive policies.

From an energy economics point of view, DER technologies are generally cost effective in most cities even though the selection of technologies varies among regions. In cities with flat electricity tariff (Lhasa, Hohhot), CHP system is generally not economic because of the low electricity tariff. However, CHP energy cost saving is especially attractive in cities where natural gas price is low. Most of cities in the West China (except Lhasa and Kunming), enjoy relatively low natural gas prices and are economically suitable for CHP system development. However, for cities with high natural gas prices, for example, Kunming, Guangzhou, Wuhan, and Harbin, CHP system is not very attractive. In these cities, application of CHP system should be restrained to small scale, or other DER technologies which are more cost-effective should be considered. The selection of absorption cooling is highly related to the availability of CHP system in order to make use of system waste heat. Heat storage device is also important to better combine CHP and absorption system, because the electricity load and cooling are not necessarily balanced during building operation hours. Solar thermal is in competition with PV due to roof area constraint, and PV is more attractive because of the subsidy. Solar thermal is only selected in limited cities, such as Kunming and Lhasa, where ample solar radiation is available. Because the prototype retail building does not have large hot water usage demand, the selection of solar thermal is very small.

It is also noticed that policies can greatly influence DER technologies selection in Chinese cities. For example, Beijing's commercial natural gas price is around 2.84 RMB/m^3, but the local government provides a special rate of 2.28 RMB/m^3. This incentive greatly promotes CHP application in commercial buildings with reasonable energy cost saving. On the electricity tariff policy side, Shanghai's electricity tariff has peak demand charge and transformer capacity charge. Even though Shanghai's natural gas price and building energy load are similar to those in the same climate region, the relatively expensive electricity cost because of demand charge means a bigger potential for CHP application in Shanghai. For renewable energy application, the government's policy of 50% cost subsidy (so called "golden sun" program) for PV system makes PV cost-wise promising in all commercial buildings in China. The subsidy also proves effective for storage technologies application. Without subsidies, PV and electricity storage devices are found to be not cost-effective.

From a CO_2 abatement perspective, DER technologies in some cities can achieve almost 40% GHG emission reduction compared with the baseline cases. The CHP system is the main GHG reduction contributor. In flat tariff cities, the CO_2 reduction is mainly produced by installation of PV. For cities in which CHP system is not selected, the emission reduction is not obvious, or in some cases, the amount of CO_2 emission gets even higher than the baseline case because of the adoption of large amount of electricity storage technology.[4]

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[4] This study assumes a static macro-grid marginal CO_2 emission factor. Because of storage leakage, the CO_2 emission reduction is not prominent. However, the on-going study also looks at dynamic marginal CO_2 emission factor which could vary in different seasons and between day and night. Under dynamic CO_2 factor as well as regional macro-grid difference, the CO_2 emission results could differ from this study.

Figure 8 Retail Building DER Technologies Energy Cost and CO_2 Abatement

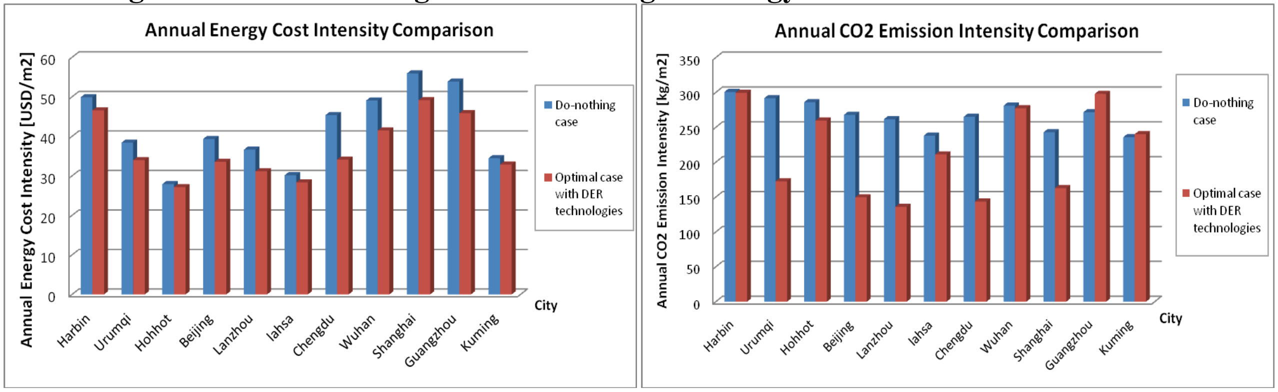

Table 4 Retail Building DER Technologies Selection

City	CHP (kW)	Battery Capacity (kWh)	Photovoltaic (kW)	HeatStorage (kWh)	AbsChiller (kW)	Solar Thermal (kW)
Harbin	250	7,427	459	0	0	0
Urumqi	1,250	2,005	459	879	311	0
Hohhot	0	0	453	5	3	30
Beijing	1,250	1,151	459	937	316	0
Lanzhou	1,250	0	459	1,040	322	0
Lhasa	0	0	424	595	7	169
Chengdu	1,250	804	459	0	288	0
Wuhan	0	13,729	459	0	0	0
Shanghai	1,250	2,322	459	0	288	0
Guangzhou	0	10,778	459	0	0	0
Kunming	0	6,027	443	139	5	79

The residential building DER technologies optimization results on cost and CO_2 emission reduction are shown in Figure 9. DER-CAM economic optimization result is shown in Table 5. Because of the flat electricity tariffs, residential prototype building only selects PV and solar thermal technologies. From heating point of view, CHP is not selected because Northern China uses district heating system. The cost of current coal-fired district heating is relatively cheap compared with making use of waste heat generated from CHP system. These factors combined makes CHP system generally not attractive in residential buildings. Chengdu, because of poor solar radiation, does not select any technology. The energy cost saving of DER is small because of limited roof area for installing these technologies. The CO_2 emission reduction mainly comes from electricity generated by PV panels.

Figure 9 Residential Building DER Technologies Energy Cost and CO_2 Abatement

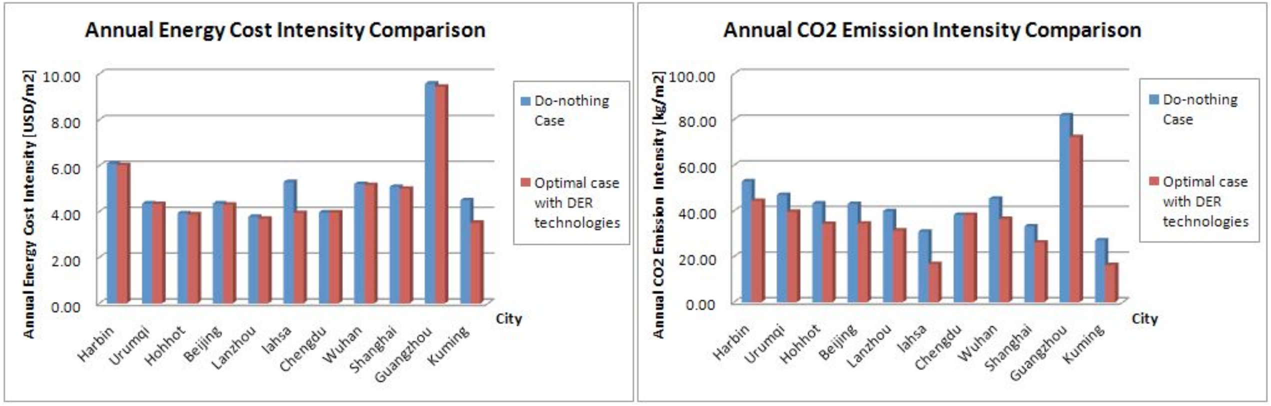

Table 5 Residential Building DER Technologies Selection

City	CHP (kW)	Battery Capacity (kWh)	Photo voltaic (kW)	Heat Storage (kWh)	Abs Chiller (kW)	Solar Thermal (kW)
Harbin	0	0	233	0	0	0
Urumqi	0	0	238	120	0	24
Hohhot	0	0	195	0	0	0
Beijing	0	0	212	15	0	36
Lanzhou	0	0	230	29	0	37
Lhasa	0	0	216	119	0	59
Chengdu	0	0	0	0	0	0
Wuhan	0	0	265	0	0	0
Shanghai	0	0	284	0	0	0
Guangzhou	0	0	330	0	0	0
Kunming	0	0	192	8	0	33

Conclusions

In general, DER technologies are more attractive in commercial buildings than in residential buildings from both an economic and GHG reduction standpoint. This is because of the difference between commercial and residential electricity tariff structure and the buildings' energy load profiles. The Chinese residential flat tariffs are generally not attractive for CHP and storage technologies. With government subsidy, PV is promising at the existing price point in both commercial and residential buildings except in regions such as Sichuan, where solar radiation is poor. Other policies, such as low natural gas price for CHP system and imposing electricity peak demand charge can also significantly affect the economics of CHP system application. In climate regions where natural gas price is low, the economics of CHP system is even better. In commercial buildings, the CO_2 emission can be reduced by about 40% on average with comprehensive DER technologies installation; while in residential buildings the reduction comes from PV application. In residential building sector, the cheap electricity tariff (in comparison with the city’s natural gas price) and, from heating point of view, the price of coal-fired district heating in Northern China make the CHP system not cost-effective.

The next step of this study is to investigate under flat electricity tariff, what natural gas tariff can make CHP system cost effective. Also, China is conducting research on residential peak, off-peak electricity tariff structure. The future study will investigate how peak, off-peak electricity tariff affects DER technologies selection, energy cost and CO_2 reduction in residential buildings.

Acknowledgment

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