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Wei Feng, Gonçalo Mendes, Shi Wang, Michael Stadler, Jan Steinbach, Judy Lai, Nan Zhou, Chris Marnay

China Energy Group
Environmental Energy Technologies Division
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Executive Summary

Energy consumed in buildings accounts for about 40% and 25% of total annual energy consumption in the United States (U.S.) and China, respectively. This paper describes a regional analysis of the potential for distributed energy resources (DER) to save energy and reduce energy costs and carbon emissions in U.S. and Chinese commercial and residential buildings. The expected economic performance of DER in the years 2020 to 2025 is modeled for a commercial and a multi-family residential building in different U.S. and Chinese climate zones. The optimal building energy economic performance is calculated using the DER Customer Adoption Model (DER-CAM), which minimizes building energy costs for a typical reference year of operation. Several types of DER, including combined heat and power (CHP) units, photovoltaics (PV), and battery storage are considered in this analysis.

Estimating the economic performance of DER technologies requires knowledge of a building's end-use energy load profiles. EnergyPlus simulation software is used to estimate the annual energy performance of commercial and residential prototype buildings in the two countries. Figures ES-1 and ES-2 show energy usage intensity for residential and commercial buildings in representative U.S. and Chinese cities.

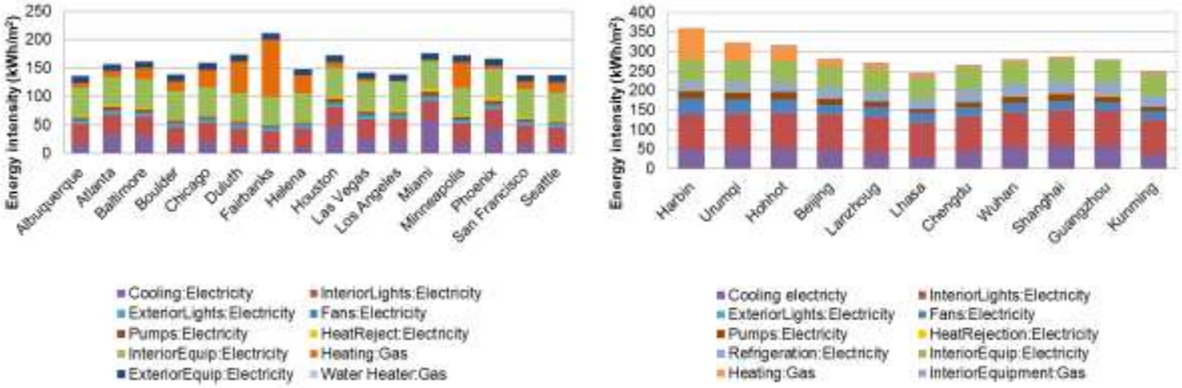


Figure ES-1 - Annual energy usage intensity of office complexes in representative U.S. cities and shopping malls in representative Chinese cities

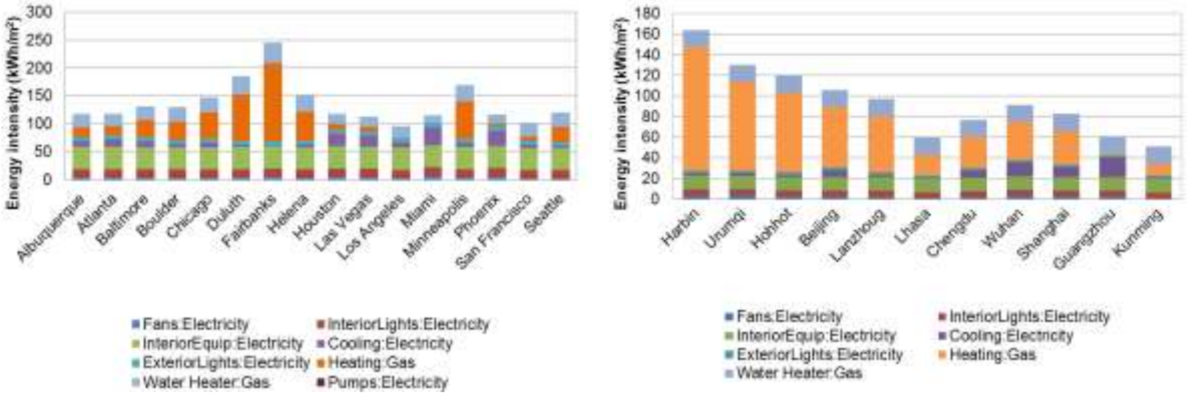
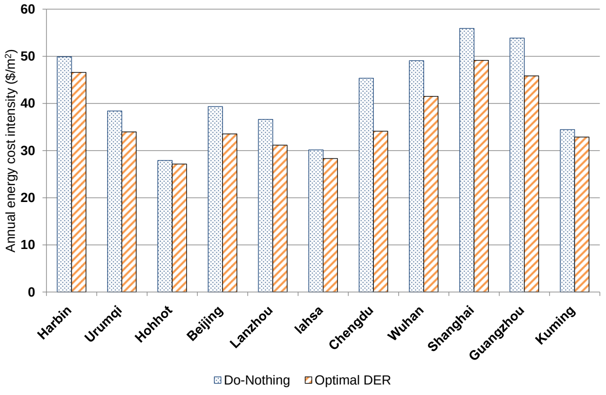
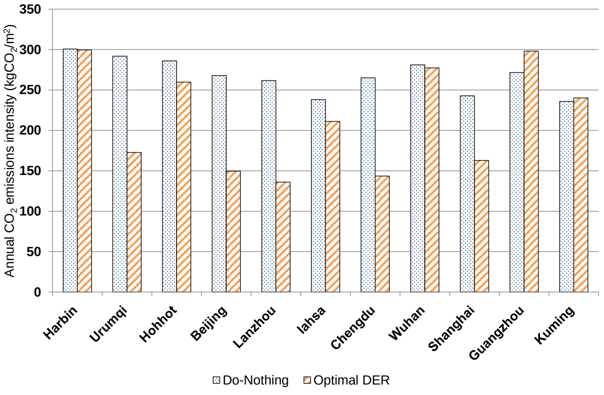


Figure ES-2 – Annual energy usage intensity of residential buildings in representative U.S. and Chinese cities

The results of the analysis (Figures ES-3, ES-4) show that various forms of DER are potentially economically and environmentally competitive, especially for commercial buildings with stable heating and/or cooling loads of both countries. The average expected energy cost reduction from DER-CAM's suggested distributed energy technologies' investments in U.S. commercial buildings is 17%; in Chinese buildings it is 12%. The attractiveness of DER depends more on the structure and prices of electricity tariffs and the cost of natural gas than on climate. In both the U.S. and China, the economic attractiveness of DER increases when spark spreads[1] are high. The average carbon dioxide (CO_2) emissions reduction in U.S. commercial buildings is 19% as a result of DER technologies adoption (such as PV); in China, the average emissions reduction is 20%, driven by investments in CHP. Some Chinese cities that rely on coal-fired electricity show significant CO_2 emissions reductions from switching to clean DER technology. In general, the analysis shows that DER technologies are better investments in commercial buildings than in residential multi-family buildings, from the perspective of both economic savings and CO_2 emissions reductions.





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[1] Spark spread is the margin between the yearly averaged price of electricity per kWh and the yearly averaged price of natural gas per kWh.

Figure ES-3 – Reduction in energy costs and CO_2 emissions intensities in Chinese commercial buildings from investment in DER (DER-CAM results)

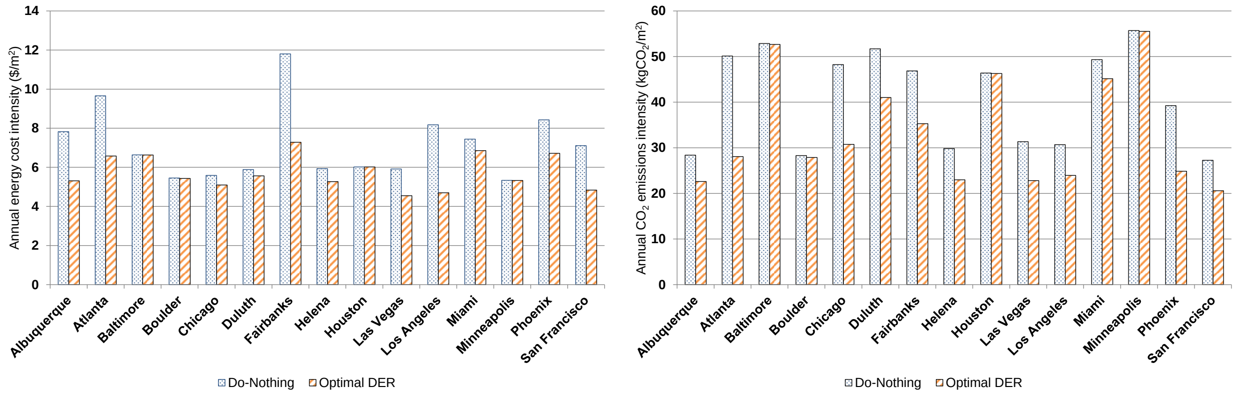

Figure ES-4 – Reduction in energy costs and CO_2 emissions intensities in U.S. commercial buildings from investment in DER (DER-CAM results, excludes Seattle)

The results also show that in U.S. cities where natural gas prices are less than 0.02-0.03 $/kilowatt-hour[2] (kWh), solar thermal is not an attractive option, but other DER heat generation choices (such as CHP) are. The model indicates that DER generation is economically attractive in cities with average electricity rates greater than 0.07 $/kWh (Figure ES-5). Analyzing whether DER would be adopted in buildings where electricity rates are lower than these values is complex, depending on climate, consumption patterns, and the way power is charged to the customer. The U.S. cities of Las Vegas, Duluth, Phoenix, and Miami fall into this category; all have an average electricity price of 0.05 $/kWh. It seems clear that when the value of spark spread is high (defined here as greater than 0.05 $/kWh), the energy savings from DER adoption are always significant (greater than 20%). The U.S. cities in this category are Fairbanks, Los Angeles, Albuquerque, and San Francisco. For lower spark spread values, this relation is not as clear. Similarly, in Chinese buildings where the spark spread is high (from around 0.08 $/kWh), there is potential to save significant energy from investment in DER (Figure ES-5).

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[2] All references to$ (dollars) in this report refer to U.S. dollars.

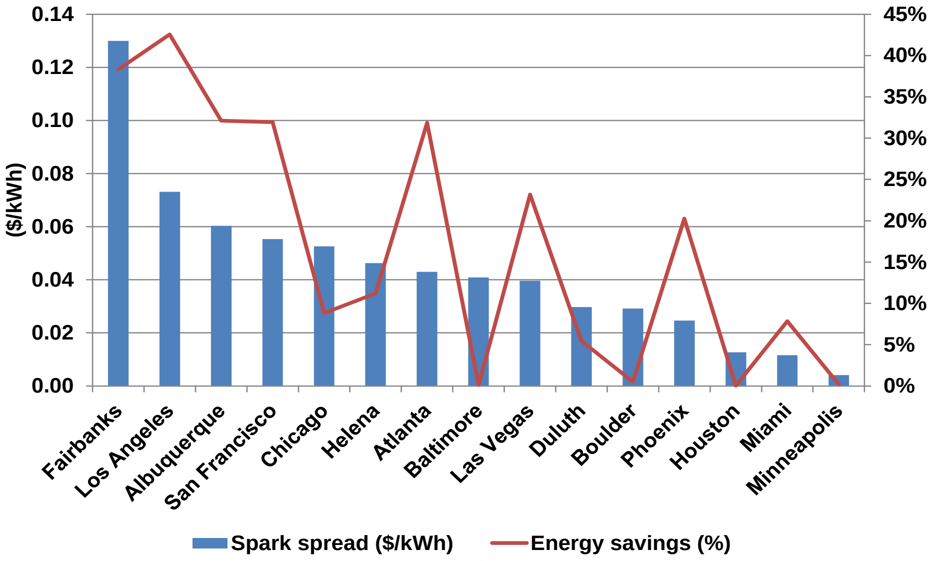

Figure ES-5 – Spark spread vs. savings analysis for DER adoption in U.S. commercial buildings

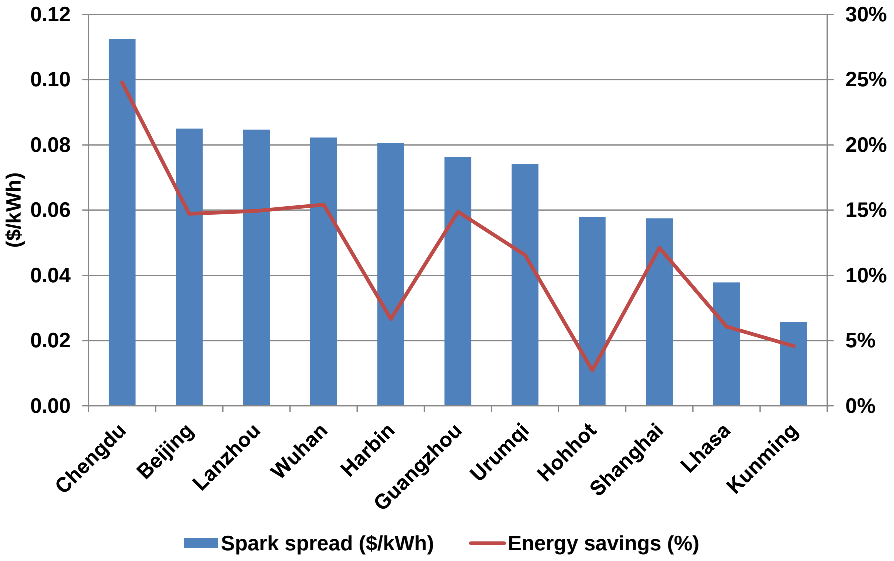

Figure ES-6 – Spark spread vs. savings analysis for DER adoption in Chinese commercial buildings

This study also investigates in depth the factors influencing the adoption of solar thermal technology in Chinese residential buildings. Each factor’s impact on solar thermal installation in residential buildings is evaluated through DER-CAM sensitivity analysis and the results are explained by using a sensitivity coefficient. The solar thermal variable cost ($/kW) sensitivity coefficient is affected by buildings’ heating load and the availability of solar radiation. As shown in Figure ES-7, the solar thermal variable cost sensitivity coefficient goes down with the buildings’ heating load. The Chinese city with the highest annual total heating demand, Harbin, is most sensitive to solar thermal technology cost. In contrast, Guangzhou, in southern China where heating demand is relatively low, is less sensitive to technology cost. Natural gas prices also play an important role in whether solar thermal technology is attractive. In general, solar thermal energy is attractive in places where natural gas prices are high. In the cities where natural gas prices are lower, customers are less likely to install solar thermal water heaters or other solar thermal technologies because these installations may not be cost effective.

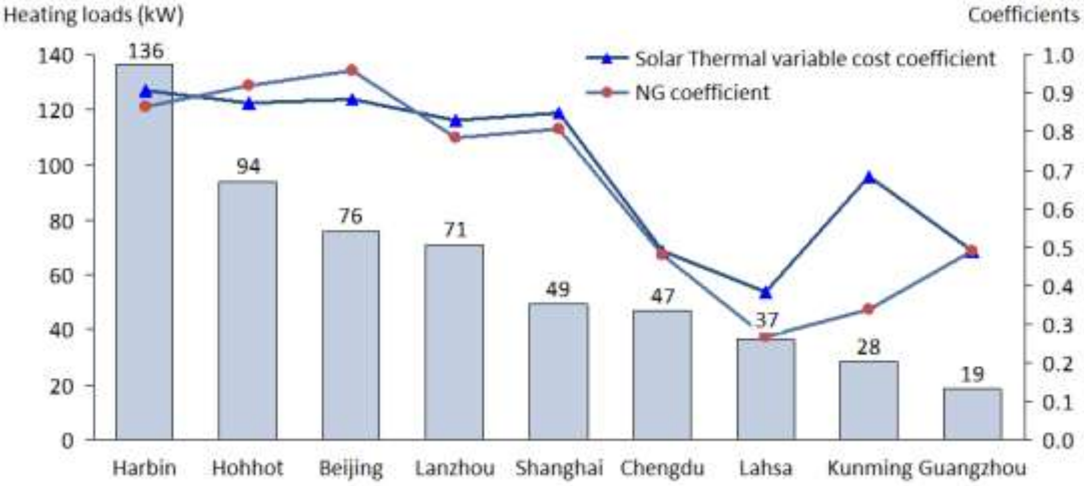

Figure ES-7 – Impact of heating load on solar thermal adoption's sensitivity to variable cost and natural gas price

Where solar radiation is ample, the price of solar technologies has less influence on whether this technology is adopted. Conversely, in places where solar radiation is limited, solar technologies will not be selected even when technology cost is low. As a result, solar thermal installation is not be sensitive to technology cost. Figure ES-8 shows the rank of sensitivity coefficients of solar thermal variable cost.

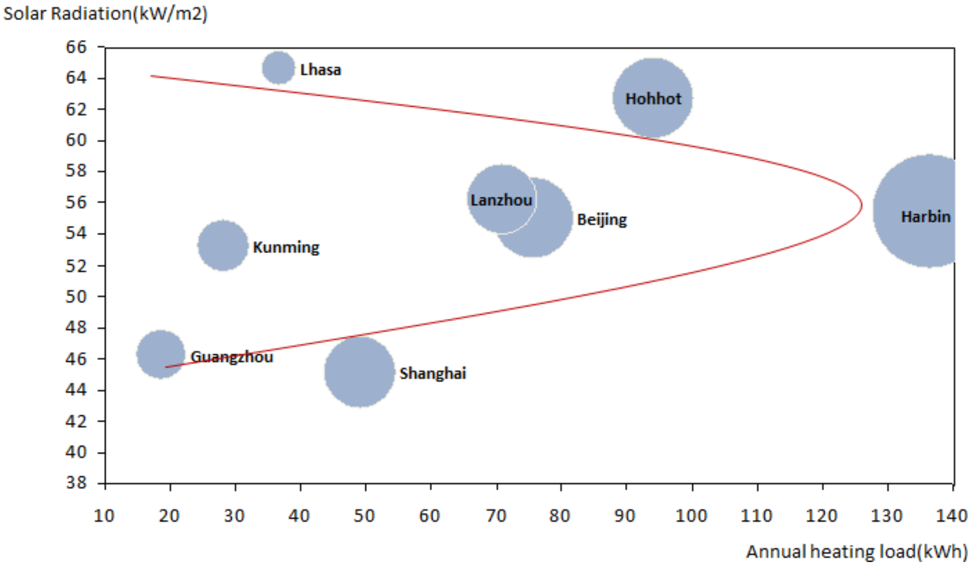

Figure ES-8 – Impact of heating load and solar radiation on solar thermal's sensitivity to variable cost

In summary, energy costs in U.S. commercial buildings were reduced by 17% as a result of the optimal DER investments modeled by the DER-CAM software. In Chinese buildings, energy costs were reduced by 12%.

If technology characteristics (such as generation efficiency, coefficient of performance and so on) are fixed, the structure and prices of electricity tariffs as well as the cost of natural gas are the most important factors determining whether DER are likely to be adopted; these factors have a stronger influence on the attractiveness of DER than does climate.

This study found that DER is potentially competitive in both warmer and colder climates. TOU tariffs, especially TOU demand charges, make DER more attractive. Very high electricity prices can stimulate DER adoption even without TOU rates.

CHP is not attractive in cities with higher natural gas prices; other DER technologies are more cost effective in this situation. The attractiveness of absorption cooling is limited by the availability of CHP and solar thermal. For both the U.S. and China, high spark spreads normally increase the economic attractiveness of DER.

In warmer climates with conducive electricity tariff structures, PV can be purchased economically, and CHP has the potential provide cooling through absorption systems. In cold areas, CHP can cost-effectively meet electrical and heating needs. Battery storage may in some cases be needed to balance mismatches between building energy loads and solar production. The economics of DER are shown to be on average more attractive in warmer areas.

In general, DER technologies are revealed to be better investments in commercial buildings than in residential buildings from both economic and CO_2 emissions reduction perspectives. The main reason for this is the difference between commercial and residential electricity tariff structures and the energy load profiles of these two types of buildings. Both the American and Chinese residential flat tariffs are generally not conducive to adoption of CHP and storage technologies; however, higher electricity prices can stimulate investments in solar PV. Solar thermal is also largely attractive in the residential context. In Northern China, the price of coal-fired district residential heating makes CHP systems not cost effective.

The results of this study show the importance of DER for abating CO_2 emissions. In the U.S., the average emissions reduction in commercial buildings from adoption of DER is 19%, mostly as a result of significant investments in PV. In China, the average emissions reduction is 20%, and investment in CHP systems is the main contributor to this reduction. When there are significant investments in electrical storage, the decline in emissions will likely be smaller because of the electricity used to charge the batteries.

From technology point of view, internal combustion engines are the preferable prime mover for CHP because they are more economic than micro-turbines but with similar efficiencies and heat-to-power ratios, and they are much cheaper than fuel cells. In China, government subsidies have proven effective in promoting adoption of PV and storage technologies, without which it was found that these technologies were not cost-effective in both retail and residential buildings. Other policies, such as low natural gas prices, can also significantly affect the economics of CHP systems, especially in climates where these systems are most attractive.

For solar thermal technology in Chinese residential buildings, the northern and eastern parts of China are more sensitive to changes in the cost of the technology. That is, if technology costs decrease in the future, residents living in these regions will be likely to adopt more solar thermal systems than those living in other regions. The southern part of China is less sensitive to technology cost. Cities like Lhasa on the Tibetan Plateau and Chengdu in the Sichuan Basin exhibit the least sensitivity to solar thermal technology costs.

Factors that may positively or negatively affect the procurement of solar thermal systems are:

- Large domestic water and space heating loads
- Abundant solar resources
- High cost of alternative energy
- Availability of area for collectors

Regression coefficients give us quantitative indicators of what will happen if technology costs decrease. In certain cities, reducing solar thermal variable cost yields promising increase of solar thermal adoption. However, the sensitivity of solar thermal adoption to its variable cost varies with building's heating load and cities solar radiation.

Solar thermal technologies compete with PV technologies in regions where prices of alternative fuels like natural gas are higher. In Guangdong, Yunnan, and Tibet provinces, it is seen more competition between these two types of solar systems if technology costs reduce or natural gas prices increase. Heat storage is the complementary technology because the combined use of solar thermal and heat storage technologies makes it possible to save the solar energy generated in the daytime for use during the evening when demand is high. Therefore, an increase in installations of one technology will boost customers' investments in the other.

Subsidies to encourage investment in solar thermal technologies should be attributed to regions sensitive to technology cost. Incentive policies, such as providing to investors a fixed amount of subsidy for each kW installed, is more effective in northern China. Prices of conventional fuels like natural gas will play an important role in customers' investment decisions. Higher natural gas prices are indirect incentives to residents to switch to solar thermal. The relationships among different distributed technologies must be considered when making policies. For example, giving incentives to both solar thermal and PV might not be effective because these two solar technologies compete for the same space, and the availability of space will limit the maximum number of solar collectors that can be installed.

Table of Contents

Acronyms

AC	alternating current
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CHP	combined heat and power
CO_2	carbon dioxide
DER	distributed energy resources
DER-CAM	Distributed Energy Resources Customer Adoption Model
EUI	energy use intensity
FYP	Five-Year Plan
kW	kilowatt
kWh	kilowatt-hours
m^2	square meter
MEF	marginal emission factor
MWh	megawatt-hour
PV	photovoltaic
RMB	Ren min bi, Chinese currency unit
TOU	time of use
U.S. DOE	United States Department of Energy

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1. Introduction

The transition from a centralized, fossil-fuel-based energy paradigm to decentralized energy supply and distribution has been a major research topic during the past two decades. The traditional model has been called into question for a number of reasons, including its environmental footprint, its structural inflexibility and inefficiency, and, more recently, its inability to maintain acceptable reliability of supply. In such a troubled setting, distributed energy resources (DER), which are small, modular, electric renewable or fossil-fuel-based electricity generation placed at or near the point of energy consumption, have gained much attention as a viable alternative or addition to the current energy system.

In the U.S. in 2010, buildings consumed 40% of total primary energy [1]. This level of energy use makes research, development, and progressive deployment of DER attractive because DER can combine the production of power and heat near the point of consumption while delivering multiple benefits, including reduced costs to customers, increased energy security, reduced environmental harm, increased market competition, and support for innovation and active engagement by consumers. Prevailing DER technologies include combined-heat-and-power (CHP)-ready reciprocating engines, micro-turbines, fuel cells, and variable renewable sources, such as photovoltaic (PV) panels.

In 2010, China's building sector consumed about 25% of the country's primary energy, leading the country to pay great attention to DER and its application in buildings. During the 11th Five-Year Plan[3] (FYP), China implemented 371 renewable energy building demonstration projects, and 210 PV building integration projects. At the end of the current (12th) FYP, China's target is to provide 10% of total building energy and to save 30 metric tons carbon equivalent of energy using building-integrated renewables. During the 12th FYP, China is also planning to implement 1,000 natural-gas-based distributed cogeneration demonstration projects with energy utilization rates greater than 70%. All of these policy targets require significant development of DER systems for buildings.

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[3] China's 11th FYP covered the period from 2006 to 2010.

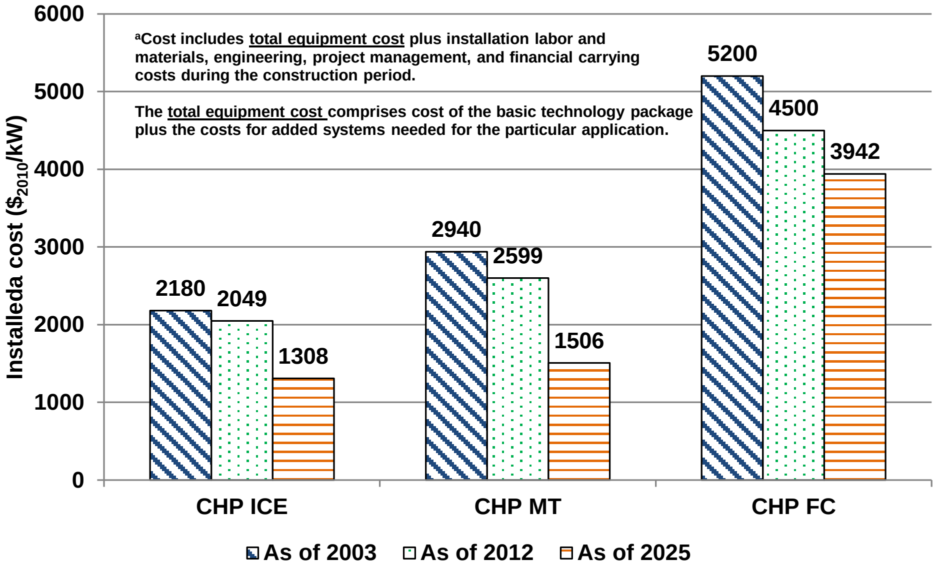

Figure 1 – Evolution of the installed costs of medium-sized CHP internal combustion engines (ICE), micro-turbines (MT), and fuel cells (FC) during the past decade, and forecast of prices for 2025 [2,3,4]

Because of an increased focus on research and development and widespread validation through pilot projects, the installed costs of DER have decreased significantly during the past decade. Figure 1 shows this trend, based on past estimates and on the Energy Information Administration price forecast for 2025. Additionally, as a result of technological advances in natural gas exploration and production, gas prices have been going down, making gas an increasingly attractive and affordable energy source for the commercial and residential sectors where electricity use still dominates [5]. Most DER units that operate using natural gas are able to capture and utilize waste heat from electricity generation, increasing their potential penetration in buildings.

Currently, the common approaches for evaluating the potential of an individual technology to save energy in a building where on-site generation is feasible are ineffective and rarely find the global optimum. In addition, to tackle climate change, government policies often promote clean technologies, such as PV or fuel cells, providing incentives for their adoption regardless 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 what are considered, by current standards, extreme efficiency measures. The cost effectiveness and energy-saving potential of these technologies are very sensitive to building energy services requirements, usage patterns, tariffs, and incentives. To holistically achieve the most cost- or carbon-effective combination of energy efficiency and on-site generation for a particular building, multiple technology options and their operating schedules need to be optimized simultaneously. Therefore, for the analysis of DER options in this report, it is modeled the optimum cost-effective combination of technologies for each type of building in each climate region, as described below.

1.1. Overview of the Research Described in this Report

Two research tasks are summarized in this report. The first task explores the potential to adopt DER technologies in commercial and residential buildings in the U.S. and China. The second task focuses specifically on the potential for adoption of solar thermal technologies in Chinese residential buildings. For the latter task, this report explores building, technological, and economic factors that influence solar thermal adoption in different Chinese climate regions.

1.1.1. Potential for DER in U.S. and Chinese Buildings

For the first research task described in this report – the potential for DER in commercial and residential buildings in the U.S. and China the Distributed Energy Resources Customer Adoption Model (DER-CAM) is used, which determines the optimal combination of technologies to supply energy needs. Modeling of distributed energy system adoption requires the following inputs: the building's end-use energy load profile, the city's solar radiation data, local electricity and natural gas tariffs, and the performance and cost of available technologies. The methodology and key assumptions used are described in the next section.

1.1.2. Potential of Distributed Solar Thermal Energy in Chinese Buildings

The second research task described in this report is an analysis of the overall potential for utilizing distributed solar thermal energy in residential buildings in different climate zones in China to achieve optimum economic and environmental benefits. For this analysis, factors including technology advances, policy directions, and market trends were considered, with the intent of giving investors and policy makers in China a view of the development potential for distributed solar thermal energy. In China, until 2009, approximately 15 billion m^2 solar thermal collectors are installed in buildings. Figure 2 shows solar thermal installation capacity in China.

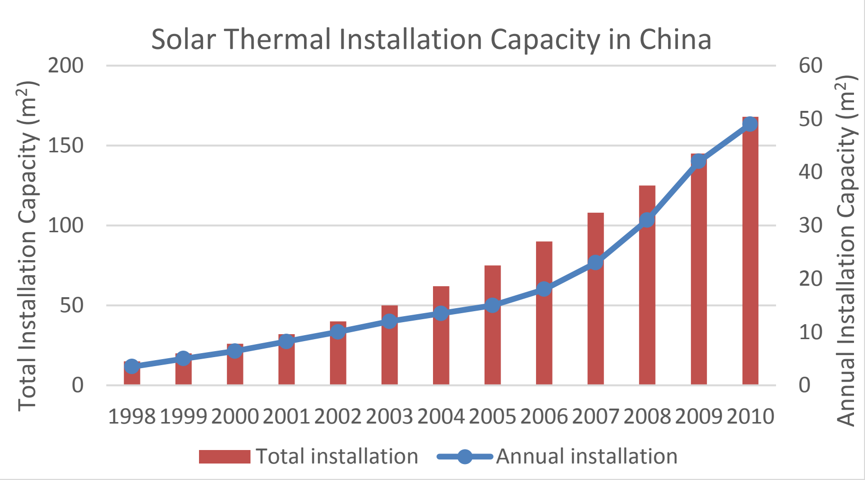

Figure 2 – Solar Thermal Installation Capacity in China

One reason for the in-depth study of the potential of solar thermal in China is that China supplies nearly half of the world's production of solar PV and thermal panels. Although the majority of products are exported, China is trying to accelerate domestic installation. The solar-powered water heater industry is well developed in China despite a lack of supporting policies between 1998 and 2008. In 2007 and 2009, two incentive policies aimed at accelerating development of the solar water heating industry were introduced. Other related technologies also show promise. Solar thermal air conditioning and heating technologies are gradually demonstrating their value, especially in distributed energy systems. Pilot projects have been implemented in various places in China[4].

The potential of solar thermal technology has blossomed as the microgrid[5] concept has made it possible to use heat as the energy form for transmission and storage. Solar thermal technologies can provide high-temperature heat that can be used for water heating, air cooling, and space heating. The combination of solar thermal panels, absorption chillers, and possibly heat-storage devices can provide buildings with solar-powered energy cycles. However, technologies using electricity or other fuels can also feed demand with energy, possibly at lower cost. Previous research has shown that, at current costs, solar thermal technology is competitive in residential buildings in China where demand for domestic hot water is high, but the technology brings less benefit in commercial buildings (Wang 2011). However, solar air conditioning can be attractive because air conditioning demand to some extent follows the solar radiation cycle of the day. For example, the Solar Air-Conditioning in Europe project concluded that solar air conditioning has a strong potential to save significant primary energy in Europe.

The main objectives of the solar thermal study described in this report are: 1) to explore, through a regional analysis, the potential of solar thermal energy in distributed applications in China, and 2) to examine corresponding policy mechanisms to accelerate the utilization of solar thermal energy.

2. Methodology

DER-CAM tool is used for this study. DER-CAM has been in development by Lawrence Berkeley National Laboratory (LBNL) for more than 10 years and has been widely used to find optimal combinations of DER technologies and to perform energy-economic assessments of DER [6,7,8]. Figure 3 shows the energy flows modeled by DER-CAM.

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[4] Solar thermal air conditioning means to use solar hot water to drive absorption chiller to provide chilled water for air conditioning.

[5] Microgrid means a grid system which can be operated as an island and connected with macro-grid.

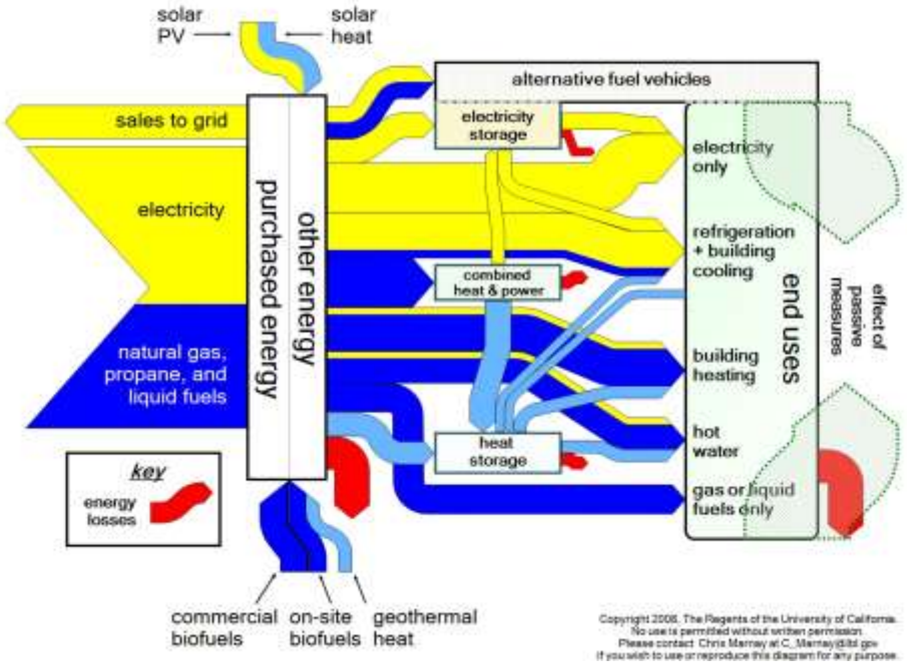

Figure 3 – Input/Output representation of DER-CAM optimization, with building energy service requirements to the right and the available energy sources to the left

DER-CAM finds the combination of supply technologies as well as the optimal operating schedule. The tool can solve the entire building energy system holistically and simultaneously in a technology-neutral manner; that is, the model seeks to minimize cost, energy use, carbon, other metrics, or a combination of metrics while considering all technology opportunities equally and equitably trading them off against each other.

2.1. Regional analysis of distributed energy resources in U.S. and Chinese buildings

In this study, DER systems in 16 representative U.S. cities and 11 representative Chinese cities were analyzed.

For the U.S. analysis, each city represents one of the 16 widely used climate zones developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Figure 4 shows the ASHRAE climate zone map, and Table 1 shows the corresponding cities ordered from warmest to coldest [9]. A weight factor is obtained for each city's specific building type based on calculating the ratio of floor space in the city's representative climate region to the country's total floor space.

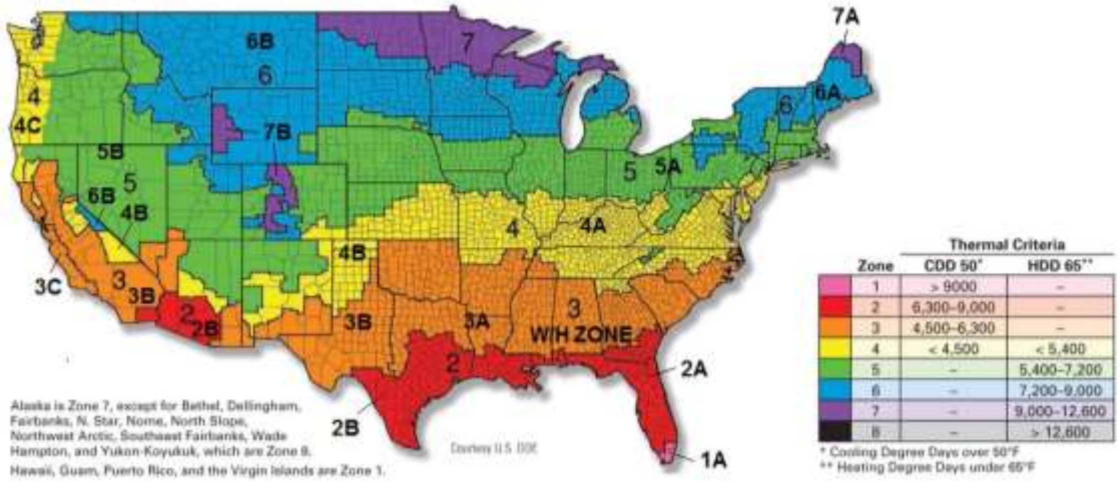

Figure 4 – ASHRAE U.S. Climate zones and respective thermal criteria (adapted from [9])

Table 1 –Representative U.S. cities with corresponding climate zones and country population weight factors (adapted from [9])

Representative city	State	Climate zone	Weight factor for large office building
Miami	Florida	1A	2.7
Houston	Texas	2A	8.6
Phoenix	Arizona	2B	1.6
Atlanta	Georgia	3A	11.8
Los Angeles	California	3B – Coast	11.7
Las Vegas	Nevada	3B	7.6
San Francisco	California	3C	3.1
Baltimore	Maryland	4A	30.0
Albuquerque	New Mexico	4B	0.0
Seattle	Washington	4C	4.1
Chicago	Illinois	5A	11.7
Boulder	Colorado	5B	3.2
Minneapolis	Minnesota	6A	3.5
Helena	Montana	6B	0.0
Duluth	Minnesota	7A	0.3
Fairbanks	Alaska	8A	0.0

Because of the U.S.'s large size and diverse geography, climate varies dramatically among zones. This is evident in the cumulative temperature curves of selected cities shown in Figure 5.

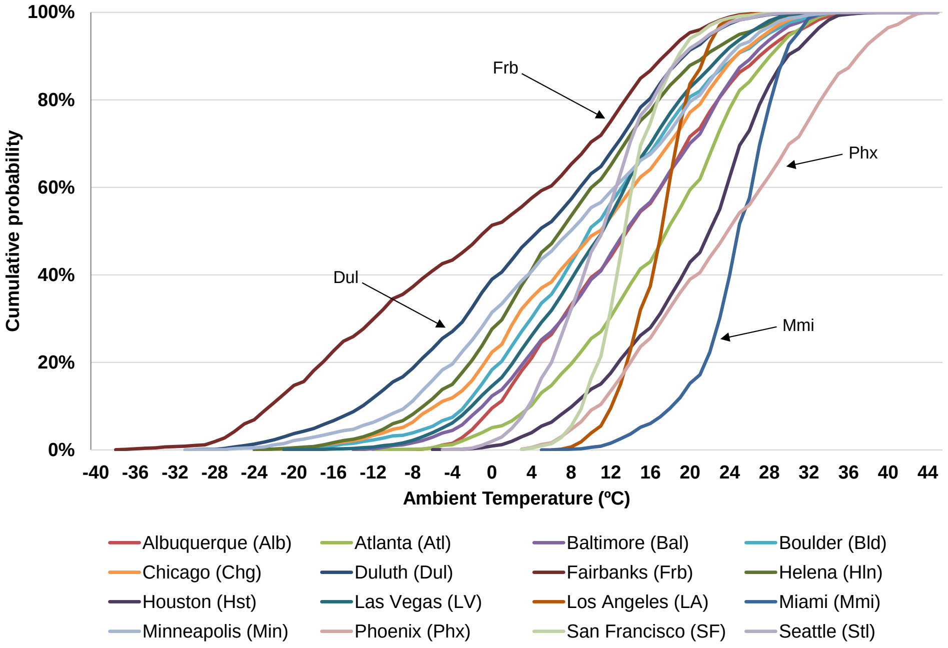

Figure 5 – Cumulative temperature distributions of representative U.S. cities

Figure 6 displays the average hourly daytime temperatures for each month of the year in the example cities of Fairbanks and Las Vegas. The differences in temperature variability between these two cities are evident. Fairbanks exhibits stable temperatures on any day of the year, with very cold winters, fairly warm summers, and a yearly average under -1ºC. In Las Vegas, there is much higher temperature variability during the day; values rarely fall under -5ºC but can reach nearly 30ºC in the summer. Figure 6 makes visible the wide range of temperatures in Fairbanks over the course of a year compared to the wide range of temperatures that are possible in Las Vegas over the course of a day.

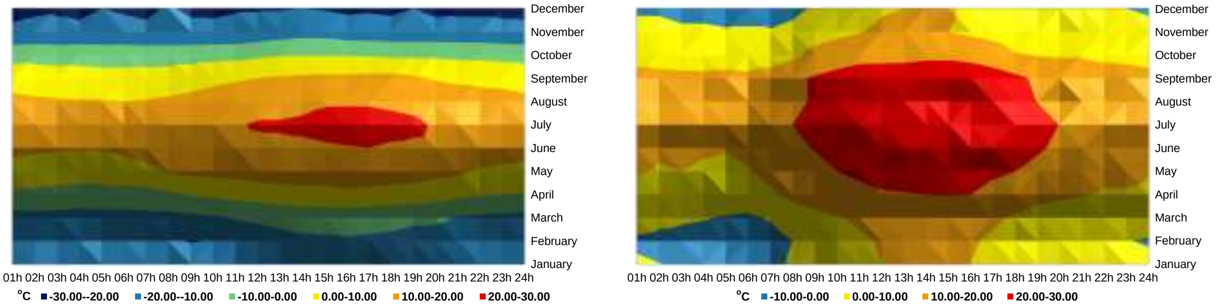

Figure 6 – Average hourly ambient temperatures by day and month, for Fairbanks (left) and Las Vegas (right)

Similarly, 11 representative Chinese cities are chosen [10]: Harbin, Urumqi, Hohhot, Lanzhou, Beijing, Lhasa, Shanghai, Wuhan, Chengdu, Guangzhou, and Kunming. Figure 7 shows the climate zone map used to select the cities, and Figure 8 plots their cumulative temperature distributions.

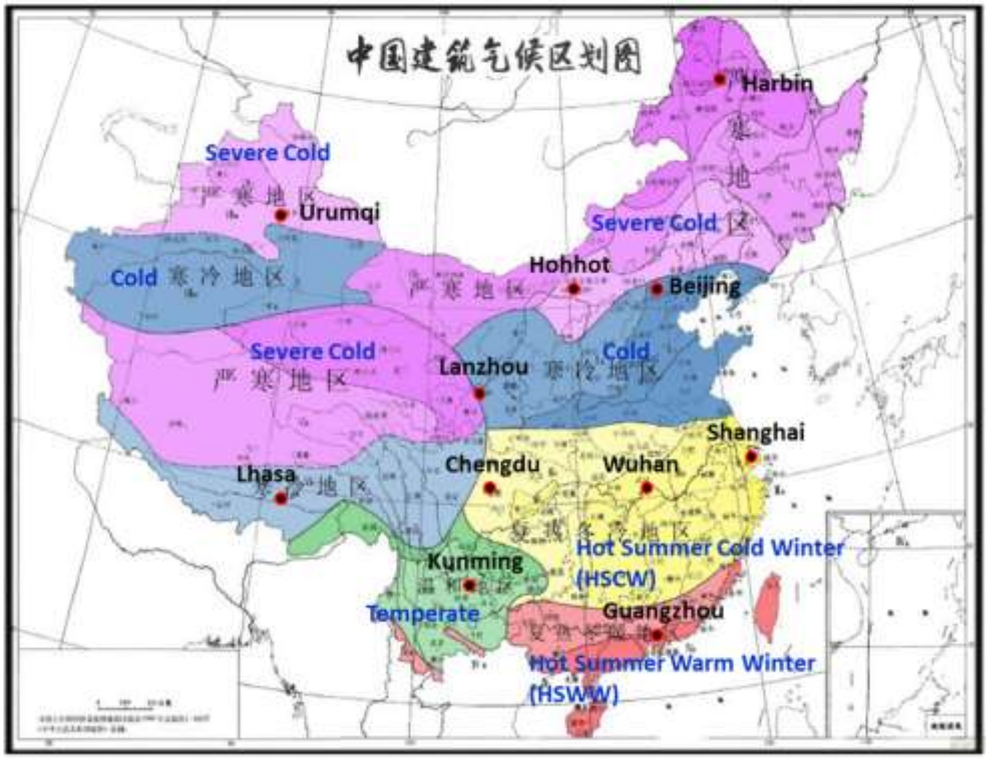

Figure 7 – China's climate zones and representative cities [10]

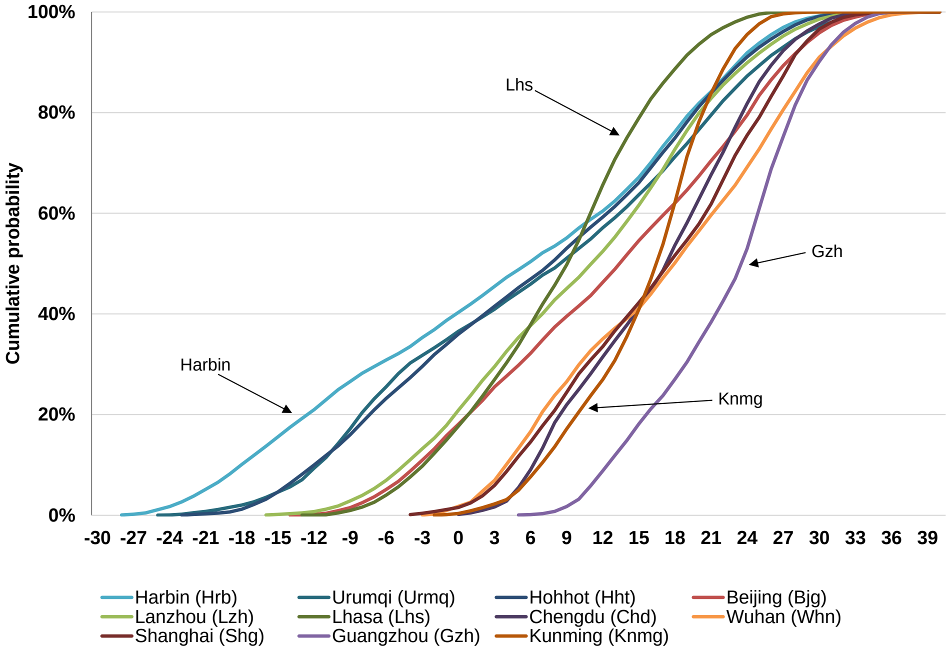

Figure 8 – Cumulative temperature distribution curves of each of the representative Chinese cities

Figure 9 shows average hourly diurnal temperatures for each month for the example cities of Harbin and Shanghai. Harbin is located in inland China, and Shanghai is in a coastal area. Both cities show strong temperature variability during any 24 hours regardless of season; however, the variability is less evident in Shanghai because of the maritime influence. Harbin, with a yearly average temperature of 4ºC, is the coldest city in the selected group whereas Shanghai's value is 17ºC. In Harbin, temperatures fall as low as -29ºC, but in the summer they exceed 30ºC. In Shanghai, summer temperatures can reach as high as 37ºC, but in the winters they can fall to -5ºC.

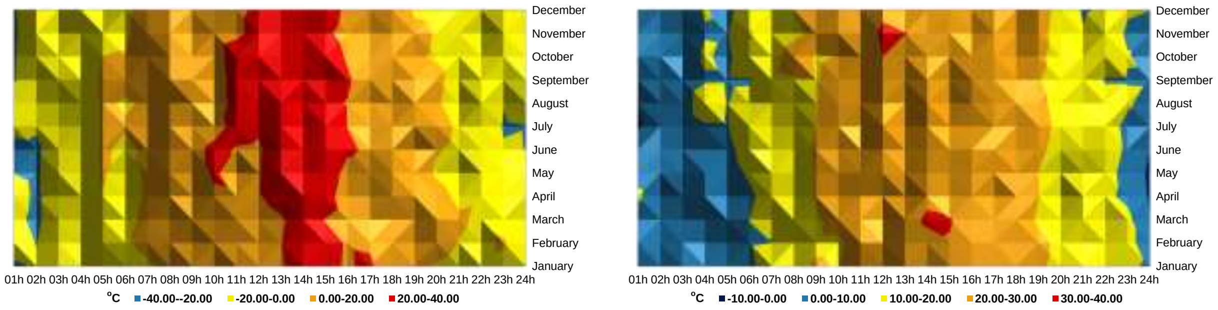

Figure 9 – Average hourly ambient temperatures by day and month, for Harbin (left) and Shanghai (right)

2.1.1. Building types

To understand building energy performance in different climate zones of the U.S. and China, two prototype buildings for each city were modeled. The American commercial buildings are taken from the U.S. Department of Energy (U.S. DOE) commercial reference buildings model set [11, 12] and correspond to a 46,320-square-meter (m^2), 12-story large office building with one basement floor, and a four-story, medium-rise, multi-family residential complex.

The Chinese buildings were a seven-story, 36,000-m^2 retail shopping center with two basement floors, and a 10-story, high-rise, multi-family building [10,13]. The commercial building prototype was developed by an on-site survey and literature review and modeled in compliance with China's Ministry of Housing and Urban-Rural Development commercial building energy-efficiency standard GB50189-2005 [14]. The residential prototype building was developed based on the U.S. DOE multi-family apartment prototype building along with Chinese studies of buildings that comply with China's residential building energy-efficiency standards. Detailed prototype building characteristics for different climate zones are described in [10].

2.1.2. Building loads

To estimate the economic performance of DER technologies, it is important to know buildings' end-use energy load profiles EnergyPlus is used to simulate the annual energy performance of U.S. commercial and residential prototype buildings [15]. Figures 10 and 11 show the energy usage intensity for U.S. and Chinese buildings by location. The cities are ordered from coldest to hottest.

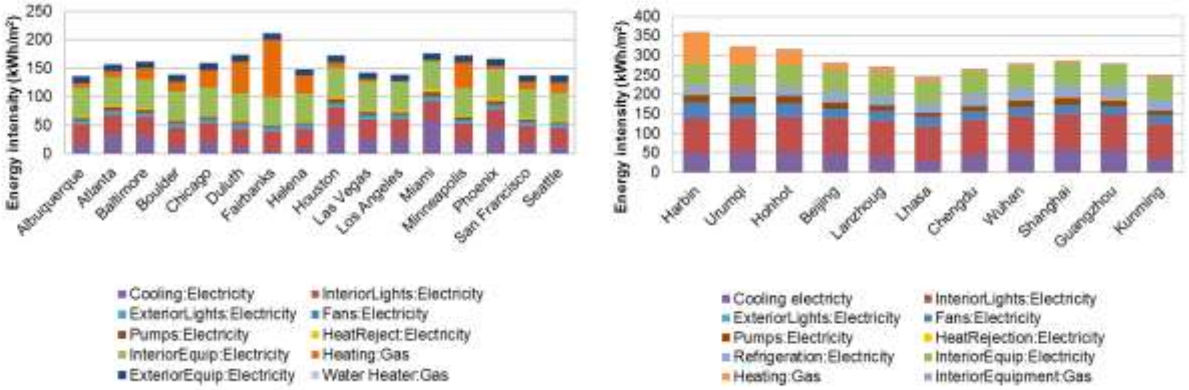

Figure 10 – Annual energy usage intensity of office complexes in representative U.S. cities and shopping malls in representative Chinese cities

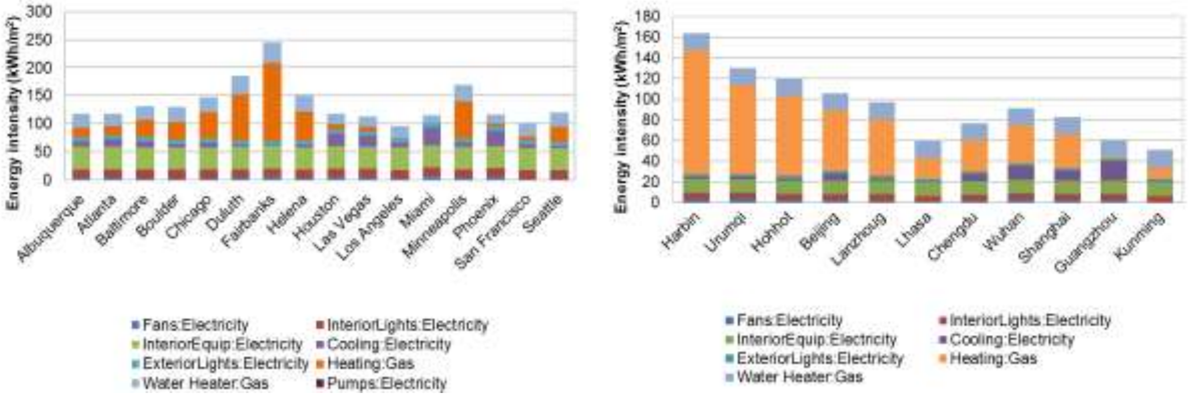

Figure 11 – Annual energy usage intensity of residential buildings in representative U.S. and Chinese cities

The figures show that, in both the U.S. and China, internal loads dominate in the commercial prototype buildings; lighting and internal equipment together consume the majority of the building's energy. In the Chinese case, the prototype building is a shopping mall with large internal loads. This type of building in China uses more energy for cooling than for heating in major climate zones, resulting in no sensitivity to climatic impacts. In contrast, a reasonable number of office buildings in colder northern areas of the U.S. consume more energy for heating than cooling. Invariably, residential buildings have lighter internal loads than office buildings and are thus sensitive to climate, as shown in Figures 10 and 11.

In China, both prototype buildings in Kunming (temperate climate zone) have the lowest energy consumption. The buildings in Lhasa (cold climate zone) use the least energy compared to buildings in other cold climate regions, mainly because of this location's high altitude and ample solar radiation. Similarly, both office and residential buildings in U.S. coastal cities with mild climates, such as Los Angeles and San Francisco, use less energy. The majority of annual energy use in the cold U.S. cities, such as Fairbanks and Duluth, is for space heating, as is the case in Harbin or Urumqi in China especially in residential buildings.

Figure 10 shows that retail buildings in China are drastically more energy-intensive than large U.S. office buildings. On average, Chinese retail building annual energy use intensity (EUI) is 287 kilowatt-hours (kWh)/m^2 whereas U.S. office buildings use only 159 kWh/m^2. In the cold Harbin climate, retail building EUIs are more than 350 kWh/m^2 while in the coldest location in the U.S., Fairbanks, the EUI is less than 250 kWh/m^2. For residential buildings, Figure 11 shows that U.S. households use, on average, 136 kWh/m^2 versus approximately 113 kWh/m^2 in China. In Fairbanks, the EUI can reach 250 kWh/m^2 while in Harbin the EUI is only 182 kWh/m^2. The difference in EUIs between the two countries is driven mainly by occupant behavior, i.e., lighting and appliance energy usage, even though U.S. building codes are more stringent than Chinese codes.

2.1.3. PV System Performance

To evaluate solar radiation and its impact on PV systems, the PVWatts on-line platform is used [16]. Figure 12 shows crystalline silicon PV performance in selected U.S. and Chinese cities. PVWatts assumes that the buildings' PV systems are mounted at a fixed tilt angle equivalent to their city's latitude, with fixed south azimuth orientation. The PV system alternating current (AC) rating is 1 kW, with an overall de-rate factor of 0.77[6], which gives a direct current (DC) rating of approximately 1.3 kW and an approximate PV system area of 11.4 m^2. The data are obtained by averaging PV system hourly AC output power on an annual basis.

One clear observation from Figure 12 is that PV system performance can vary significantly from one region to another; this affects the economics of PV. Albuquerque, Las Vegas, and Phoenix enjoy high rates of solar irradiation and therefore higher potential PV performance than other cities. Chinese cities with similar levels of irradiation are Hohhot and Lhasa; however, because China has only one time zone, the peak PV production time differs across regions. As Figure 12 also indicates, the range of PV performance is slightly higher across U.S. cities, from 0.5 kWh to 0.9 kWh of hourly peak power generated.

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[6] The overall de-rate factor is calculated by multiplying de-rate factors of components such as the inverter and transformer, AC and DC wiring, and taking into account soiling and age.

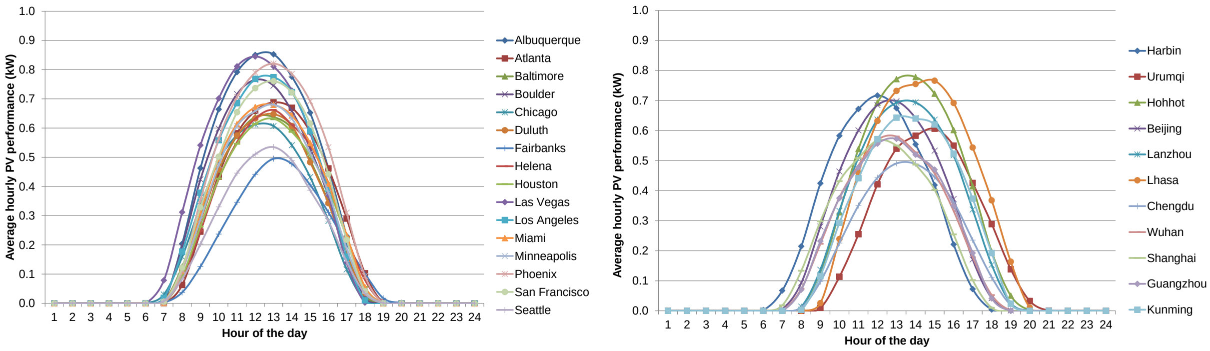


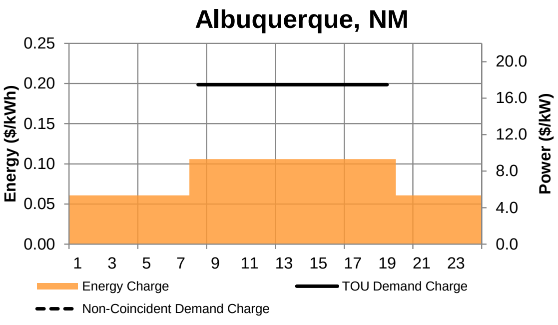
Figure 12 – Comparison of PV System Performance in U.S. and Chinese cities

One feature that limits the adoption of PV is available physical space for installation, which differs from one building type to another. On large office buildings, the available area is about 16,200 m^2 whereas on the mid-rise residential buildings, the area is 3,300 m^2.

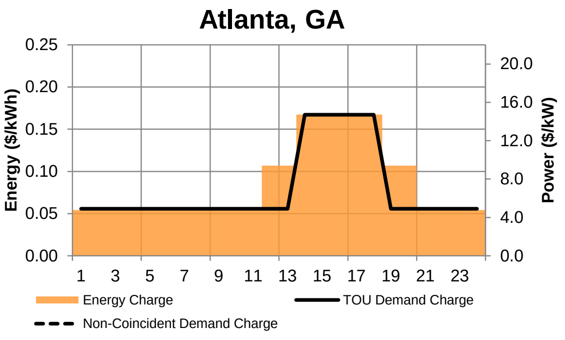
2.1.4. Tariffs

The structure of U.S. commercial electricity tariffs is complex, and average prices vary significantly among regions. In most cities, there is a time-of-use (TOU) rate, added to a fixed monthly customer cost and power demand charge and split into summer and winter periods. Demand charges can be set during certain TOU time periods or, in other cases, may not coincide with a load peak but instead may be applied to the largest number of kW used during any period of the month.

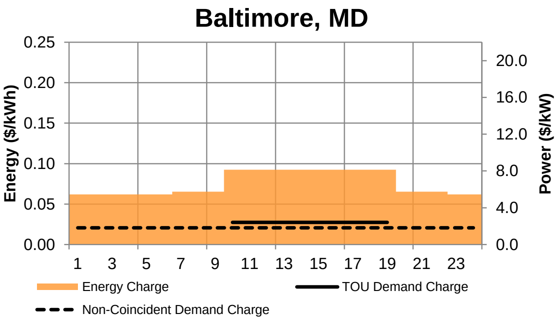
For this study, 2012 commercial electricity rates were collected from utilities serving the reference U.S. cities. A number of utilities, such as Atlanta and Baltimore, offered TOU tariffs, and others, for instance Duluth and Chicago, had simpler schemes with flat energy charges. All tariffs, whether TOU or non-coincident (flat), include demand charges. Figures 13a) to 13p) show summer-day electricity rate schedules for each of the U.S. reference cities.


Albuquerque, NM
Energy ($/kWh)
0.25
0.20
0.15
0.10
0.05
0.00
Power ($/kW)
20.0
16.0
12.0
8.0
4.0
0.0
1 3 5 7 9 11 13 15 17 19 21 23
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

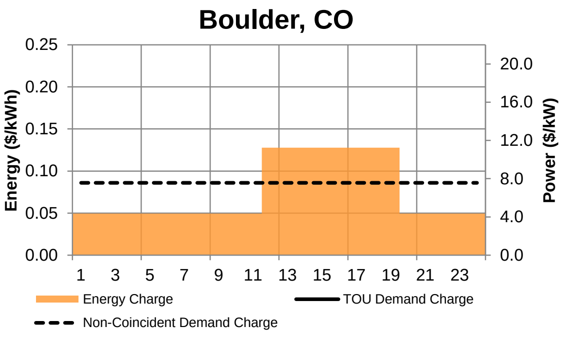
a)


Atlanta, GA
Energy ($/kWh)
0.25
0.20
0.15
0.10
0.05
0.00
Power ($/kW)
20.0
16.0
12.0
8.0
4.0
0.0
1 3 5 7 9 11 13 15 17 19 21 23
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

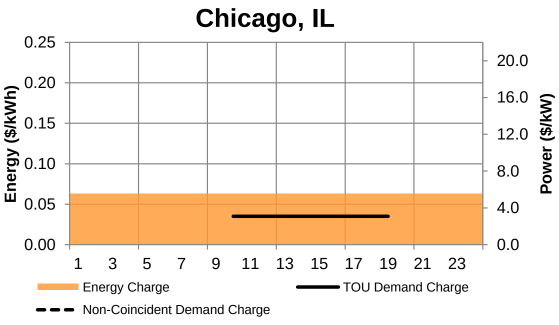
b)


Baltimore, MD
Energy ($/kWh)
0.25
0.20
0.15
0.10
0.05
0.00
Power ($/kW)
20.0
16.0
12.0
8.0
4.0
0.0
1 3 5 7 9 11 13 15 17 19 21 23
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

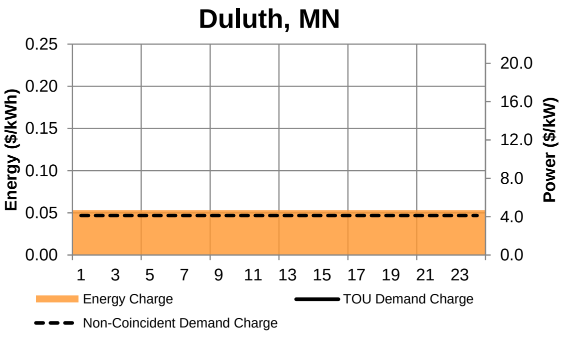
c)


Boulder, CO
Energy ($/kWh)
0.25
0.20
0.15
0.10
0.05
0.00
Power ($/kW)
20.0
16.0
12.0
8.0
4.0
0.0
1 3 5 7 9 11 13 15 17 19 21 23
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

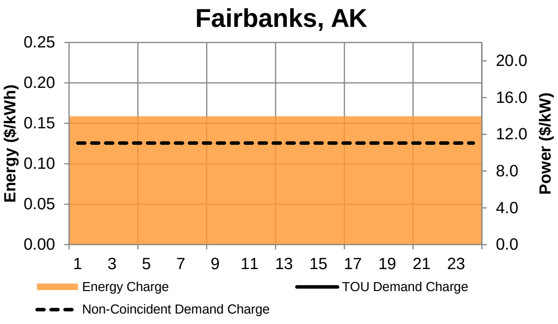
d)


Chicago, IL
Energy ($/kWh)
0.25
0.20
0.15
0.10
0.05
0.00
Power ($/kW)
20.0
16.0
12.0
8.0
4.0
0.0
1 3 5 7 9 11 13 15 17 19 21 23
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

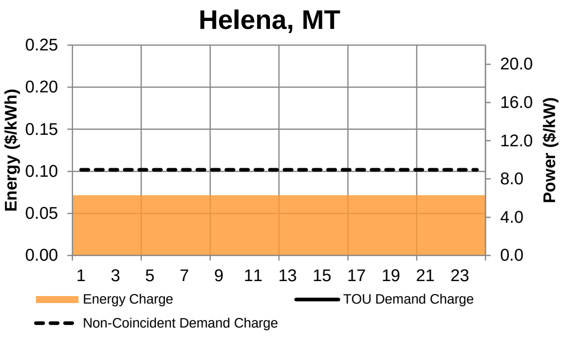
e)


Duluth, MN
Energy ($/kWh)
0.25
0.20
0.15
0.10
0.05
0.00
Power ($/kW)
20.0
16.0
12.0
8.0
4.0
0.0
1 3 5 7 9 11 13 15 17 19 21 23
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

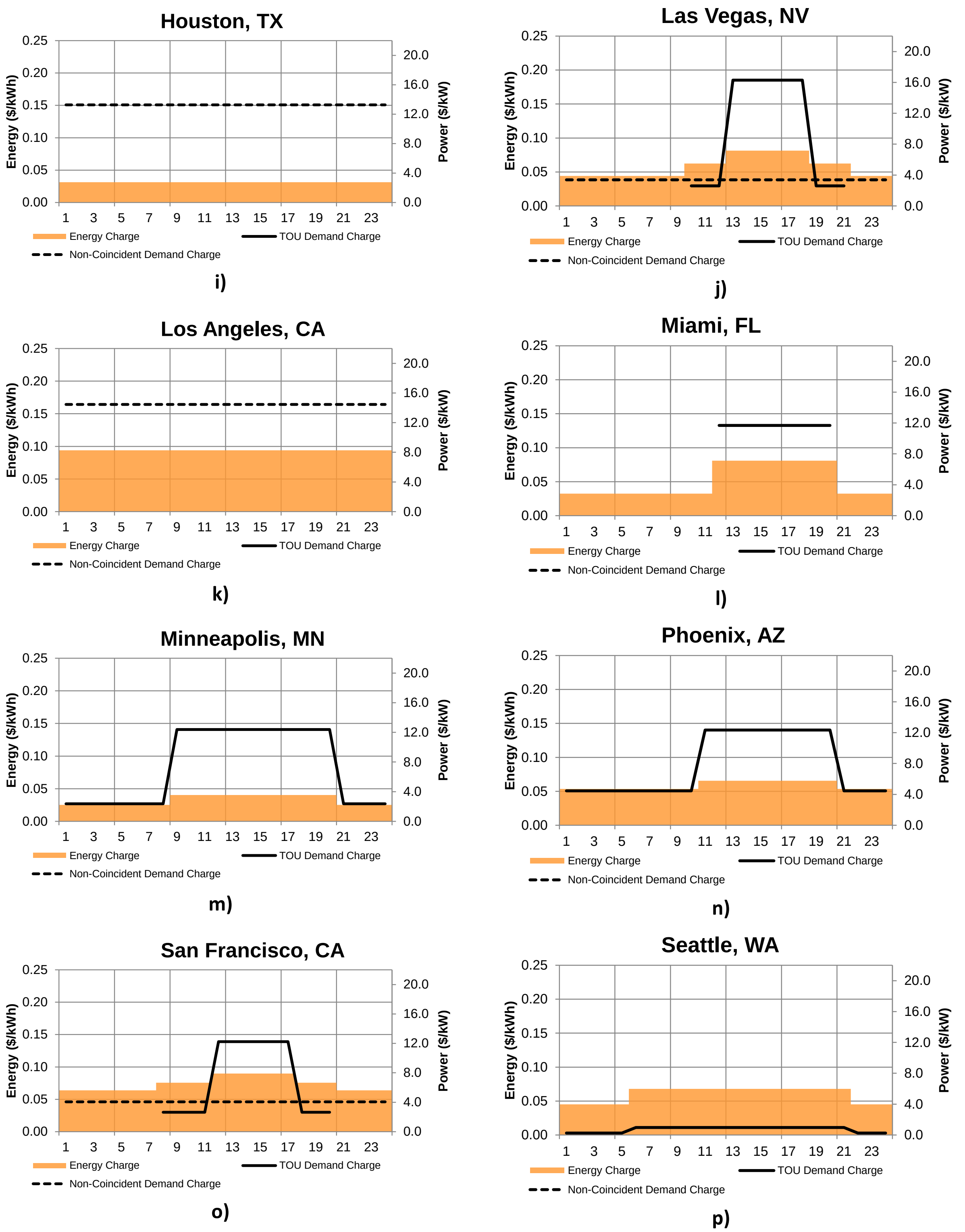
f)


Fairbanks, AK
Energy ($/kWh)
0.25
0.20
0.15
0.10
0.05
0.00
Power ($/kW)
20.0
16.0
12.0
8.0
4.0
0.0
1 3 5 7 9 11 13 15 17 19 21 23
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

g)


Helena, MT
Energy ($/kWh)
0.25
0.20
0.15
0.10
0.05
0.00
Power ($/kW)
20.0
16.0
12.0
8.0
4.0
0.0
1 3 5 7 9 11 13 15 17 19 21 23
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

h)



i) j) k) l) m) n) o) p)

Figure 13 – Office building electricity and power charges for a summer day in each U.S. reference city

The structure of electricity rates is a determining factor in DER adoption. U.S. electric utilities and their regulators use various strategies for charging customers, which adds complexity to the demand patterns of a given zone. Normally, between energy and power charges are balanced, with the latter tariffs being either TOU or non-coincident. As an example, in Houston the energy pricing is flat and quite low (0.03 $/kWh[7]) in comparison to pricing in other cities. However, the utility in Houston features one of the highest non-coincident demand charges (13.26 $/kW) in the studied group. Albuquerque has an even higher demand charge (17.47 $/kW) but only during peak times. In Albuquerque case, energy charges are also TOU, in the range of 0.06 to 0.11$/kWh. This is true for the utilities serving Las Vegas and Atlanta as well. Some utilities also charge for power using both TOU and non-coincident tariffs, as in Baltimore and San Francisco. Some schedules exhibit maximum energy pricing sophistication, including not only both types of demand charges but also three-period TOU volumetric rates. Lastly, in Alaska, where the electricity system relies heavily on old diesel generators, energy costs more than in all the other reference climate zones; for example, in Fairbanks the summer energy flat rate is 0.16 $/kWh.

Residential tariffs are generally simpler. They consist of flat energy rates, usually with values close to 0.08-0.09 $/kWh, as in the case of Miami and Houston, but they can exceed 0.11 $/kWh, as in San Francisco, Baltimore, Phoenix, and Las Vegas. In some cases, these tariffs are also seasonal.

Figure 14 shows (for a summer day) the electricity tariffs used for Chinese commercial buildings. In China, most cities have summer and winter rates; cities with hydropower also have drought, rainy, and intermediate season rates. On a daily basis, most cities, except Hohhot and Lhasa, have peak, off-peak, and intermediate rates for commercial buildings, as shown in Figure 14. Demand charges are not very common in Chinese cities. In a city such as Shanghai, the demand charge is non-coincident with a rate of 40.5 (RMB)/kWh (6.5 $/kWh)[8]. In the residential sector, a flat tariff is common although some cities have TOU rates.

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[7] All dollar ($) values in this report are in U.S. dollars.

[8] In this study, we use a currency conversion rate of 1 $US = 6.5 RMB.

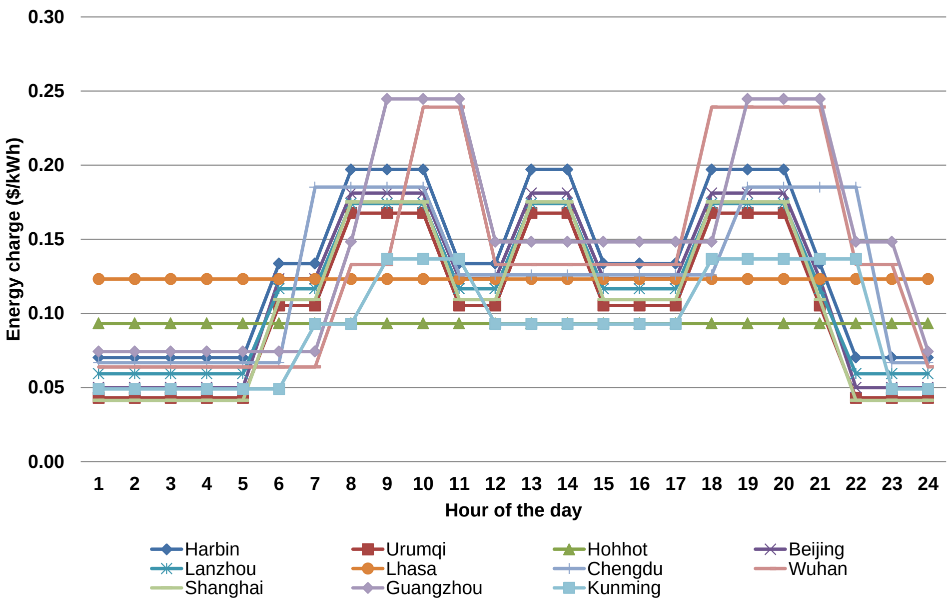

Figure 14 – Electricity tariffs for a summer day in Chinese cities

Natural gas tariffs for residential and commercial buildings in the U.S. and China are shown in Figures 15 and 16, respectively. In China, commercial natural gas tariffs are usually slightly higher when compared to residential tariffs in the same city. In the U.S., except in Boulder, larger customers have lower tariffs. This is particularly noticeable in this study because large office complexes are compared to small residential buildings. Cities in the western and central areas of China (with the exceptions of Kunming and Lhasa) have relatively lower natural gas rates than those in eastern regions. Likewise, Figures 15 and 16 show that China's natural gas prices are higher overall. The differences between electricity and natural gas costs in both the U.S. and China suggest the need to look closely at the energy pricing spark spread[9] for each city. Because both electricity and gas prices are higher in Chinese cities than in U.S. cities, the spark spreads are relatively close those in U.S. cities. In the U.S., values are as high as 0.13 $/kWh in the extreme case of Fairbanks. In China, the minimum spark spread is about 0.03 $/kWh in Kunming and about 0.11 $/kWh Chengdu. The average in the Kunming case is 0.04 $/kWh and in the Chengdu is 0.07$/kWh.

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[9] Spark spread is defined as the margin between the yearly averaged price of electricity per kWh and the yearly averaged price of natural gas per kWh.

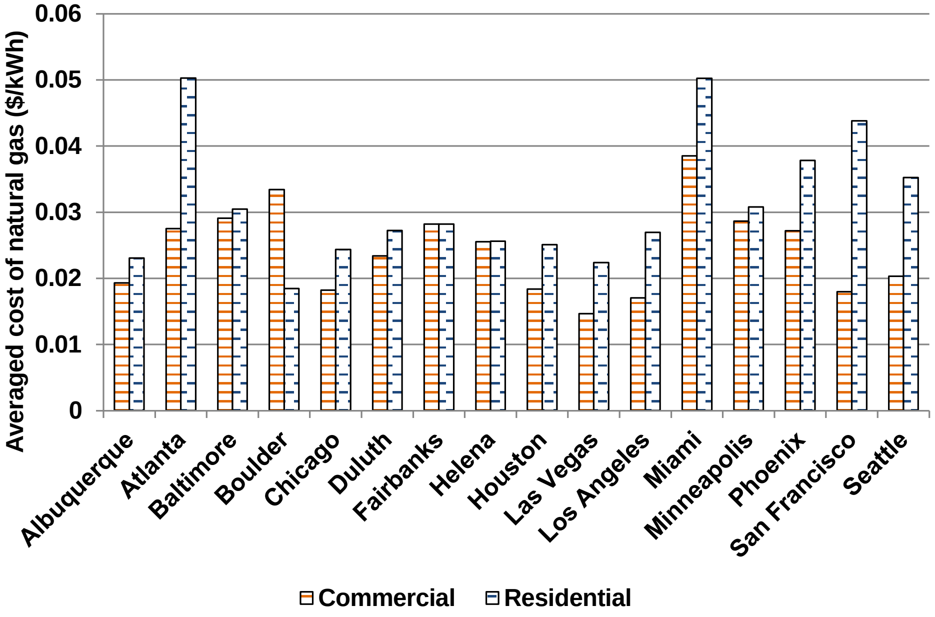


Figure 15 – U.S. commercial and residential natural gas tariffs

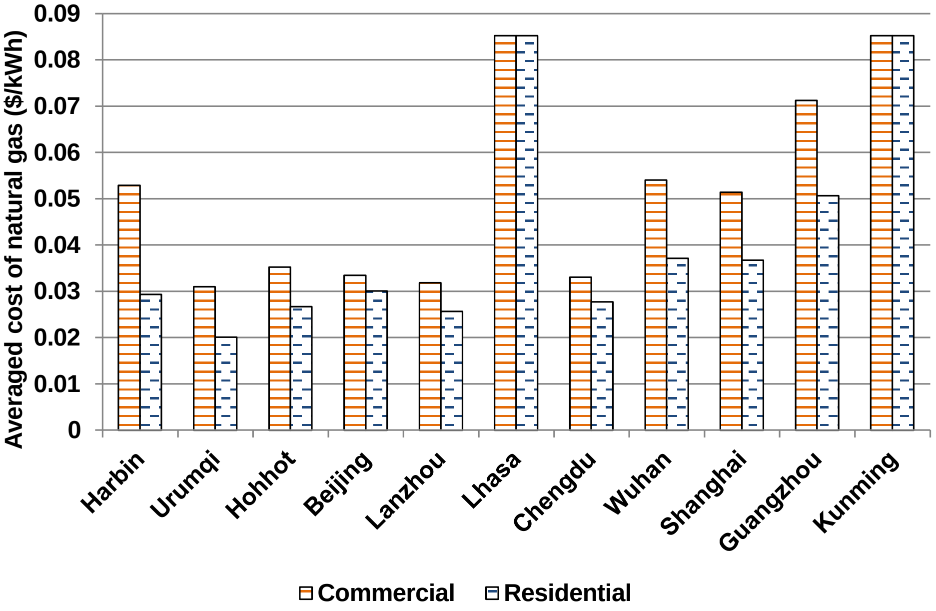


Figure 16 – Chinese commercial and residential natural gas tariffs

For purposes of modeling the adoption of natural-gas-fired DER, the prices shown in Figure 15 might not reflect a sufficiently detailed reality because a few U.S. utilities [17, 18, 19] have started to use self-generation tariff schedules that apply to residential and commercial customers owning renewables, engines, micro-turbines, or fuel cells. These tariffs are intricate, and in some cases there are specific, complex agreements between customers and the utility. Furthermore, this service can be provided in bundled or unbundled form although the latter is usually the preferred option. In unbundled arrangements, the customer purchases natural gas from a trader at city-gate price levels and is charged by the utility for use of its distribution network. Customers with DER contracts are invariably able to purchase natural gas at more attractive prices than customers who do not have such contracts. For the optimization of DER resources performed in this study, it is assumed that natural gas for DER electricity generation in the U.S. is purchased at a price that is 10% lower than the costs shown in Figure 15. This is a conservative assumption when compared to reported savings of up to 40% in energy charges for natural gas when DER tariffs are adopted [19,20].

2.1.5. Technology cost and performance

Techno-economic characteristics of DER equipment are key in determining which technologies are suitable and economically attractive in different cities. The optimization modeling runs apply the expected performance and cost characteristics of DER in years 2020 to 2025 (Tables 2 and 3). Table 4 shows the performance parameters used for electrical and heat storage systems.

Table 2 – DER CHP technologies techno-economic characteristics [2, 4]

CHP Technologies	Capital cost ($/kW)	Lifetime (years)	Efficiency (%)	Heat/Power Ratio	O&M Cost ($/kWh year)
ICE 60kW	1,591	20	33	1.77	0.022
ICE 250kW	1,308	20	36	1.48	0.018
MT 60kW	1,632	10	34	1.77	0.014
MT 150kW	1,506	10	36	1.59	0.016
FC 100kW	4,245	10	47	1.19	0.033
FC 250kW	3,942	10	52	0.89	0.037

Notes: All technologies run on natural gas. ICE - Internal Combustion Engine, MT – Micro-turbine, FC - Fuel Cell, O&M – operation and maintenance). Efficiency refers to the electrical conversion efficiency of the equipment.

Table 3 – DER storage, cooling, and renewable technology costs [2, 8, 10]

Technologies	Intercept Fixed Cost ($)	Variable Cost ($/kW or $/kWh for storage)	Lifetime (years)	O&M Cost ($/kW or $/kWh for storage)
Electrical Storage				
U.S.	295	193	5	0.00
China[a]	0	100	5	0.00
Heat Storage				
U.S.	10,000	100	17	0.00
China[a]	10,000	50	17	0.00
Absorption Chiller	20,000	127	15	1.88
Photovoltaics				
U.S.	0	2,495	25	0.25
China[a]	0	1,615	25	0.25

Solar Thermal						
U.S.	0		284	25		0.50
China [a]	1,000		400	25		0.50

Note: Electrical Storage refers to conventional lead-acid batteries.

[a] Price is subsidized in China with 50% cost-sharing through governmental incentives.

Table 4 – Energy storage parameters [8]

Technologies	Electrical Storage	Heat Storage
Charging efficiency	0.90	0.90
Discharging efficiency	1.00	1.00
Decay [a]	0.001	0.01
Maximum charge rate	0.10	0.25
Maximum discharge rate	0.25	0.25
Minimum state of charge	0.30	0.00

Notes: All parameters are dimensionless. [a] The decay value is relatively high because the lifetime of lead-acid batteries is assumed at its upper end when the decay increases rapidly.

The performance and cost parameters used in the analysis for CHP technologies in China are similar to those in the U.S. However, PV, solar thermal, and storage devices have different pricing than in the U.S. and are subsidized in China. The Chinese "Golden Sun" Program pays 50% of the investment cost for installing PV and solar thermal equipment. It is also assumed a 50% subsidy for battery electric and heat storage in China.

Finally, to estimate DER technologies' impact on greenhouse gas emissions reduction, it is necessary to address the marginal emissions associated with purchasing electricity from the grid. Table 5 shows the main grid systems in China and their marginal emission factors (MEFs) for CO_2 [21[10]]. Because China's electricity is mostly generated from coal, emission factors are generally higher than those in the U.S. and other developed countries. The right-hand side of Table 5 shows the MEFs for electricity generated from the U.S. grid. Because these MEFs mostly depend on the generation mix of a given system, the CO_2 emission factors are characteristic of each North American Electric Reliability Corporation sub-region. Each of these regions includes several U.S. states but shares a single interconnection. Siler-Evans et al. [22] characterizes in detail the marginal emissions of U.S. generation.

Table 5 – U.S. and Chinese grid CO_2 marginal emission factors[11] [10, 22, 23]

Region[a]	CO_2 MEF ($kgCO_2/kWh$)	Region	CO_2 MEF ($kgCO_2/kWh$)

---

[10] This study considered only the CO_2 emissions from fossil-fuel-sourced electricity generation.

[11] Due to absence of detailed data, this study assumes a static macrogrid marginal CO_2 emissions factor, which is an approximation of reality. Marginal emissions from the grid vary slightly during the different seasons of the year and between day and night hours. If a dynamic marginal emission factor is considered, the CO_2 emission results could differ from those in this study.

U.S.		*China*	
FRCC	0.532	**North Grid**	0.980
MRO	0.834	**Northeast Grid**	1.085
RFC	0.731	**East Grid**	0.837
SERC	0.680	**Central Grid**	1.030
TRE	0.527	**Northwest Grid**	1.000
WECC	0.486	**South Grid**	0.949
SPP	0.596		
NPCC	0.489		
ASCC	0.581[b]		

[a] *FRCC – Florida Reliability Coordinating Council , MRO – Midwest Reliability Organization, RFC – ReliabilityFirst Corporation, SERC – SERC Reliability Corporation, TRE – Texas Reliability Entity, WECC – Western Electricity Coordinating Council, SPP – Southwest Power Pool, NPCC – Northwest Power Coordinating Council, ASCC – Alaska Systems Coordinating Council*

[b] *For the Alaskan Grid, this value corresponds to the total averaged system output emissions rate, which is a fair approximation to the marginal emission factor.*

2.2. Solar thermal sensitivity analysis in Chinese residential buildings

Adoption of solar thermal technology in buildings is influenced by numerous factors and shows strong regional differences. Tariffs for electricity and natural gas vary among regions in China because of natural resource distribution and other factors (e.g. energy transportation cost). Solar radiation is more plentiful in provinces in western China, such as Tibet, Qinhai, and Xinjiang, In the eastern coastal areas, there is much less solar radiation. Figure 17 is a map of the distribution of solar radiation in China. Population density and industrial activities are greater in eastern and southern China, and this area accounts for a dominant portion of total energy demand. Despite the lower level of radiation in the east, more than two-thirds of China has abundant solar resources and thus these areas are candidates for distributed solar energy development. Because of the variations in conditions across China, a regional analysis is important for evaluating how solar thermal installations in buildings are affected by energy load, tariffs, solar thermal technology costs, and competition from other technologies.

To conduct this regional analysis, it is used the same residential buildings and climate zones as discussed in the previous sections of this report. Simulated building energy load profiles are modeled in DER-CAM to determine regional sensitivity; sensitivity variables were generated at random to cover reasonable ranges.

The methodology for the sensitivity analysis was as follows: a series of random values was used to create a DER-CAM project file, and a program was developed to perform DER-CAM optimizations and export the results. Multiple runs were conducted with different sets of random values. Figure 18 shows how sensitivity runs are conducted using DER-CAM.

Figure 17 – Distribution of China's solar radiation resources

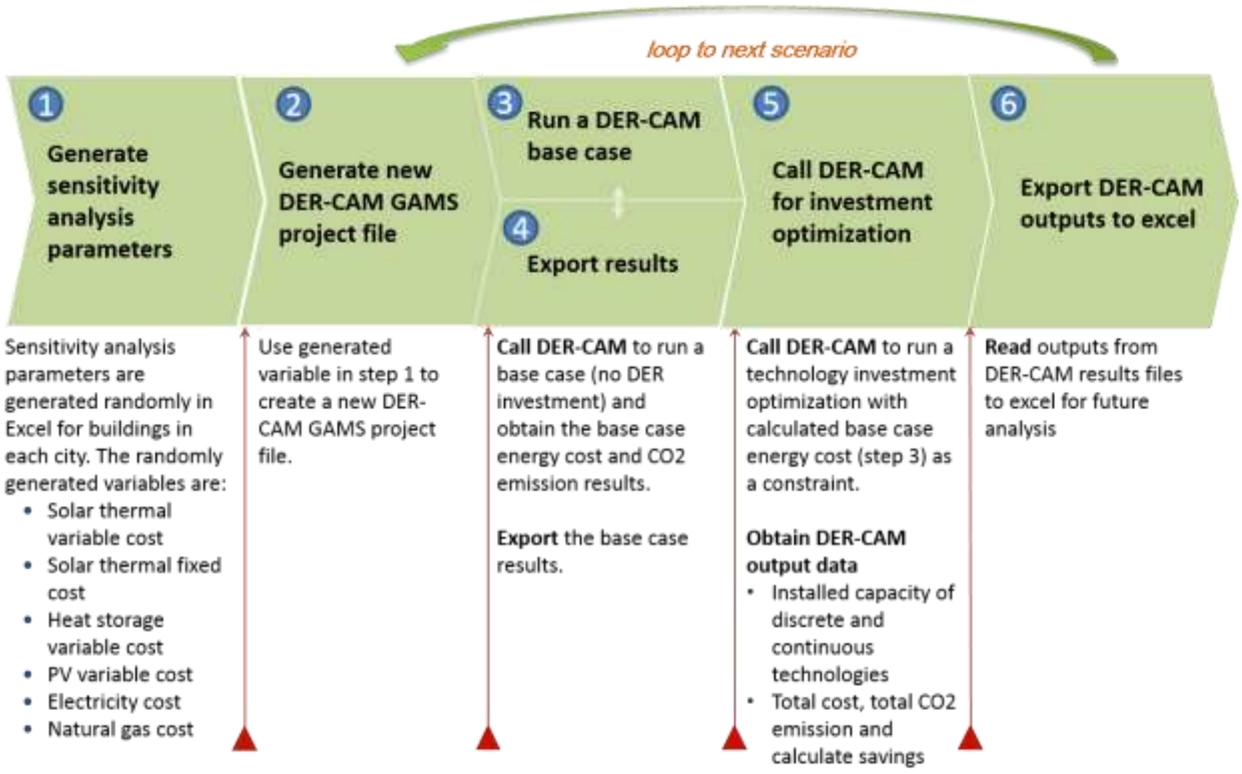
2.2.1. Large-volume DER-CAM runs

In repeated DER-CAM runs, all of the explanatory variables changed values randomly within a given range for each run. In the model, a sample that is 15 times larger than the number of variables is generated by random numbers within a certain pre-set range. A sample of 90 is used in the residential buildings analysis for each city. Results are organized in and developed in a multi-linear regression model, and further analysis are made based on simulation results. Results collected from DER-CAM simulations are analyzed statistically to differentiate the factors that affect the installation of solar thermal technology. With current technology costs, tariffs, and other inputs, some technologies will be adopted in the DER-CAM simulation output, and others will not. The costs of the technologies that are adopted under current conditions are considered as explanatory variables for the sensitivity analysis. Supporting policies such as up-front subsidies can be included in technology cost variables. Other policies, such as mandated installation, are applied on a regional basis. Figure 18 shows the sensitivity run procedure. Sensitivity variables are generated in step 1. In step 2, a set of DER-CAM project files are generated using random generated sensitive variables. A baseline DER-CAM run is conducted in step 3 and results are exported in step 4. In step 5, a set of DER-CAM optimization runs are executed and the results of each run are exported for analysis.

The variables for residential building solar thermal sensitivity analysis are:

- Solar thermal variable cost

- Solar thermal fixed cost
- Heat storage variable cost
- PV variable cost
- Electricity energy cost
- Natural gas energy cost



Sensitivity analysis parameters are generated randomly in Excel for buildings in each city. The randomly generated variables are:

- Solar thermal variable cost
- Solar thermal fixed cost
- Heat storage variable cost
- PV variable cost
- Electricity cost
- Natural gas cost

Use generated variable in step 1 to create a new DER-CAM GAMS project file.

Call DER-CAM to run a base case (no DER investment) and obtain the base case energy cost and CO2 emission results.

Export the base case results.

Call DER-CAM to run a technology investment optimization with calculated base case energy cost (step 3) as a constraint.

Obtain DER-CAM output data

- Installed capacity of discrete and continuous technologies
- Total cost, total CO2 emission and calculate savings

Read outputs from DER-CAM results files to excel for future analysis

Figure 18 – DER-CAM sensitivity runs process

2.2.2. Sensitivity analysis

After collecting data from 90 sensitivity runs in each city, a linear regression on these data with Stata software is performed. Stata is an integrated statistical package that provides data analysis, data management, and graphics. The linear regression model is the most widely used for econometric analysis. It specifies the conditional mean of a response variable *y* as a linear function of *k* independent variables:

$$\mathrm{E}[\mathrm{y}|x_1, x_2, \dots, x_k] = \beta_1 x_1 + \cdots + \beta_k x_k$$

The regression is used to estimate the unknown effect of changing one variable versus another. The β_i are fixed parameters; the linear regression model predicts the average value of *y* in the population for different values of x_1, x_2,…x_k

The key assumptions when using multiple linear regression models are that there is a linear relationship between two variables (i.e. x and y), and this relationship is additive (i.e. $y = x_1 + x_2 + \cdots + x_n$).

In the study of solar thermal potential in China, the dependent variable is solar thermal installed capacity, which is given by DER-CAM optimization solutions. The independent variables are chosen based on previous analysis: solar thermal fixed and variable costs, heat storage costs, PV costs, and electricity and natural gas prices.

$$\begin{aligned} InstalledsolarThermalCapacity \\ = \beta_1 \cdot SolarThermalVarCost + \beta_2 \cdot HeatStorageCost + \beta_3 \cdot PVCost + \beta_4 \\ \cdot ElectricityTariff + \beta_5 \cdot NaturalGasTariff + \beta_6 \cdot SolarThermalFixedCost \end{aligned} \tag{1}$$

The β_i in the equation reflect the degree to which installed solar thermal capacity is sensitive to each of the independent variables. In theory, this sensitivity will vary in different cities because of load profile and climate characteristics. The signs of β_i represent the positive or negative impact of the independent variables on the dependent variable. If β_i is positive, the corresponding independent variable will have a positive impact on *y*, which means that when the independent variable increases, the solar thermal installed capacity will increase as well. Within all six variables, PV cost is expected to have a positive impact on solar thermal installed capacity because a rise in PV cost will reduce the installed capacity for PV technology and might cause an increase in solar thermal installations when the maximum roof area for installed solar technologies (e.g. PV, solar thermal) is reached. If β_i is negative, the impact of the independent variable on *y* is negative. The expected impact of the solar thermal variable and fixed costs is negative because solar thermal technology will be less competitive if its cost increases while other technologies' costs remain unchanged.

3. Results and Discussion

Table 6 shows the optimal technologies that DER-CAM selected for U.S. commercial buildings, based on annualized technology investment cost, energy consumption cost, energy conversion performance, and renewable energy harvest. Figure 19 illustrates commercial building energy cost optimization results and associated CO_2 abatement potential, expressed in terms of energy and emissions intensity. For each city, there is a baseline "do nothing" case, which reflects a situation in which electricity and natural gas are purchased from the local utilities, and buildings use electric chillers for cooling and natural gas for space heating. There is greater sensitivity to climate in the U.S. than in China, which affects DER adoption.

3.1. U.S. commercial-sector results

DER-CAM found an economically feasible mix of DER technologies for most U.S. cities. The average energy cost reduction from the optimal solutions is 17%. The exception is Seattle where no economic improvement is achievable from investment in DER. The influence of electricity tariffs is evident in Seattle where there are only minimal demand charges, and the volumetric rate is relatively low and only slightly variable, behaving almost as a flat tariff. Also, Seattle has a low natural gas tariff, which creates an obstacle to investment in solar thermal, which is an attractive technology in other reference cities.

3.1.1. Limited savings and DER investments in cities with cheap electricity or no TOU tariff

In a few cities, namely Baltimore, Boulder, Houston, and Minneapolis, DER-CAM identified no or only limited electric generation DER. The only significant economically attractive investment identified for these cities was in solar thermal generation. Consequently, these cities showed very limited savings (a maximum of 1%). Houston and Minneapolis have two of extreme climates in the group of cities studied, which indicates that the energy price or tariff structure there does not promote DER adoption. In fact, Houston has one of the lowest electricity energy charges and no TOU differential. In the cold Minneapolis region, electricity is equally cheap; even though a TOU tariff is available, it is not enough to stimulate substitution of DER generation for electricity purchased from the current utility. Boulder and Baltimore represent moderate climate areas where the absence of significant TOU demand charges diminishes the attractiveness of DER. However, investment in solar thermal is attractive in these two cases. All of the remaining cities have very attractive conditions for DER.

3.1.2. Large energy savings in cities with warmer climates

A number of warmer cities with attractive tariffs, notably Phoenix and Atlanta, have opportunities for significant investment in PV. Other cities in this group are Albuquerque, Las Vegas, Los Angeles, and San Francisco. In this group, the whole DER system average energy cost reduction is 30%; in Los Angeles, where there are no TOU demand charges, the reduction in annual energy costs is 43%. This seems to contradict the expectation that flat tariffs would not induce investments in DER. However, in Los Angeles, the electricity and the non-coincident demand charges are so high that utility power cannot compete with the economics of DER. Looking at the whole group of solutions proposed by DER-CAM, it is seen that the maximum available area for solar system deployment in buildings is never reached, which suggests that competition between PV and solar thermal is not very fierce. In Miami, the warmest city, investment in PV is not economically viable because of low electricity costs. The largest suggested investment is in CHP and battery storage, producing a cost reduction of a merely 8%. DER not only meets the electricity-only requirements but also feeds absorption chillers to supply Miami's pronounced cooling needs. In all cites (including Fairbanks) with the exception of Duluth, DER-CAM identified absorption systems as an economic means of providing cooling.

3.1.3. In cold climates, DER is less attractive

In colder climates, namely in Fairbanks, Duluth, Helena, and Chicago, DER are less attractive than in warmer areas, but there are cost-effective options to invest in CHP to meet the heating requirements of the buildings, and in battery-storage to balance the electrical supply, with total average savings of 16%. Fairbanks attains by far the largest savings from DER adoption, overall a 38% reduction in total annual energy costs. This is expected, considering the high electricity costs in Alaska. All investments in CHP are in internal combustion engines, which are more economic than micro-turbines for similar efficiencies and heat-to-power ratios, and much cheaper than fuel cells. The DER-CAM results also show that heat storage is not widely attractive given the technical-economic characteristics under consideration.

3.1.4. Larger energy savings in cities with high spark spreads

In cities with natural gas prices less than 0.02-0.03 \$/kWh, solar thermal is not an attractive option whereas other heat-generation DER options are attractive. In cities with average electricity rates greater than 0.07 \$/kWh, DER generation makes economic sense. Determining whether cities with electricity rates lower than the above values would adopt DER generation is complex, depending on climate, consumption patterns, and the way power is charged to the customer. The cities of Las Vegas, Duluth, Phoenix and Miami are in this category; all have average electricity prices of 0.05 \$/kWh. However, when looking at the spark spread in each of the cities (shown in Figure 20 in the next section), it is seen that, for high spark spread values (defined here as greater than 0.05 \$/kWh), the energy savings from DER adoption are always significant (more than 20%). Fairbanks, Los Angeles, Albuquerque, and San Francisco are in this category. For lower spark spread values, this relation is not as clear.

3.1.5. DER's significant potential to abate CO_2 emissions

From a CO_2 -abatement perspective, DER's enormous potential is obvious in Figure 19. The average emissions reduction in the American buildings is 19%, but customers in Phoenix and Atlanta achieve reductions of 40% and more because of significant investments in PV. CHP uses fuel more efficiently than other technologies; this is also a relevant factor in emissions reduction, notably in Chicago but also in Las Vegas, San Francisco, Fairbanks, and Duluth. In Miami, where DER-CAM suggests significant investment in CHP and battery storage, the reduction in CO_2 emissions is interestingly low, approximately 8%. The cause is significant investment in electrical storage that uses utility electricity to charge batteries, which increases grid marginal emissions.

Table 6 – U.S. Commercial buildings optimal DER technologies

Representative city	CHP (kW)	Electric storage (kWh)	PV (kW)	Heat storage (kWh)	Absorption Chiller (kW)	Solar Thermal (kW)	Energy gen. on site (MWh/annum[a])
Albuquerque	500	0	118	0	218	0	1,888
Atlanta	500	0	464	0	192	20	2,068
Baltimore	0	0	1	0	0	33	1
Boulder	0	0	6	0	0	56	13
Chicago	500	27	0	0	114	0	1,900
Duluth	310	0	4	0	0	0	835
Fairbanks	560	51	0	0	128	0	1,796
Helena	560	83	72	0	119	0	1,794
Houston	0	0	0	0	0	16	0
Las Vegas	560	0	187	0	214	0	2,296
Los Angeles	560	101	130	0	203	0	2,410
Miami	750	265	0	0	202	20	1,303

Minneapolis	0	0	0	0	0	38	0
Phoenix	560	0	442	0	186	76	2,597
San Francisco	560	48	119	0	175	0	1,979
Seattle	0	0	0	0	0	0	0

[a] megawatt-hours per year

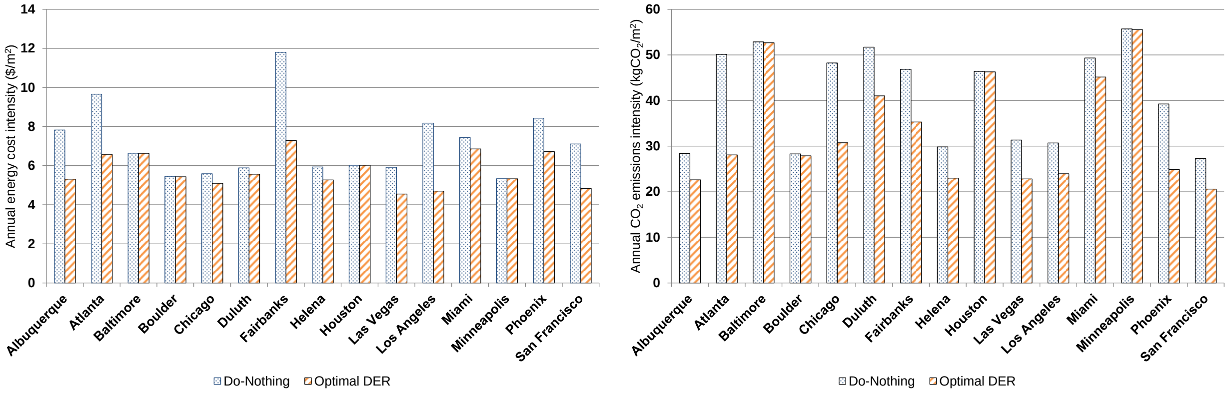


Figure 19 – Abatement of energy cost and CO_2 emissions intensities in U.S. commercial buildings through investment in DER (DER-CAM results, excludes Seattle)

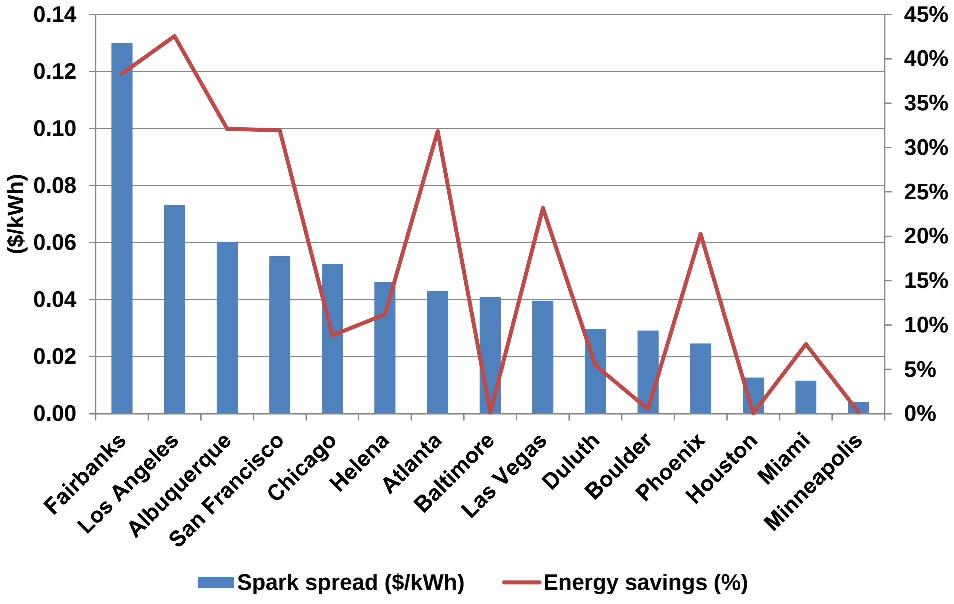


Figure 20 – Spark spread vs. savings analysis for DER adoption in U.S. commercial buildings

3.2. China commercial sector results

DER technologies are cost effective in retail buildings in most of the Chinese cities studied (listed in Table 7 and Figure 21), achieving energy savings of 12% on average. The selection of technologies varies among regions; some are similar to U.S. cases described above.

3.2.1. Natural gas and electricity pricing structure strongly affects CHP adoption

CHP reduces energy costs, especially in cities where natural gas prices are low. In cities with flat electricity tariffs, for example Lhasa and Hohhot, CHP systems are generally not economic. Most of the cities in western China (except for Lhasa and Kunming), enjoy relatively low natural gas prices, which makes CHP systems economically attractive. In Beijing where commercial natural gas price is subsidized, this subsidy makes CHP very attractive, and its adoption results in reasonable energy cost reductions. Regarding electricity tariffs, Shanghai's tariff includes peak demand charges and a transformer capacity charge. Even though Shanghai's natural gas price and building energy loads are similar to those in China's other climate regions, electricity is relatively expensive because of the demand charge, which makes CHP applications attractive. In Kunming, Guangzhou, Wuhan, and Harbin where natural gas prices are higher, CHP systems are not attractive. DER-CAM proposed heat storage in some buildings because storage allows for an effective combination of CHP and absorption cooling systems. This is justified by the existing time gap between the electricity and cooling loads, which are not necessarily balanced during building operation hours. Because of limited roof area, solar thermal competes with PV, which is more attractive because of the government subsidy. Solar thermal is recommended in only a few cities, such as Kunming and Lhasa, where ample solar radiation is available. The prototype retail building does not have a large hot water demand, which limits solar thermal's attractiveness.

3.2.2. High spark spread can lead to larger DER investments

The spark spread vs. savings analysis in Figure 22 indicates that customers in areas with high spark spreads (in the case of China, 0.08 $/kWh or more) can save significant energy from investment in DER. However, certain exception may apply to different cities where the TOU energy tariff, demand charge, and buildings' energy load profile vary from one to another.

3.2.3. CHP as main driver for CO_2 emissions abatement in China

DER technologies can reduce CO_2 emissions by 40% in some Chinese cities compared to baseline cases. CHP systems are the main contributors to this emissions reduction because of the higher marco-grid marginal emission factors in China than in the U.S. Examples of these reductions are in retail buildings in Beijing and Chengdu. In buildings in cities where tariffs are flat, e.g. Lhasa and Hohhot, the CO_2 emissions reduction mainly results from installation of PV. For buildings in which a CHP system is not selected, the emissions reduction is not obvious. In some cases (Harbin, Wuhan, and Guangzhou), CO_2 emissions increase over the "do-nothing" case because of the adoption of large amounts of electricity storage.

Table 7 – Chinese commercial buildings optimal DER technologies

Representative city	CHP (kW)	Electric storage (kWh)	PV (kW)	Heat storage (kWh)	Absorption Chiller (kW)	Solar Thermal (kW)	Energy gen. on site (MWh/annum)
Harbin	250	7,427	459	0	0	0	1,666
Urumqi	1,250	2,005	459	879	311	0	6,775
Hohhot	0	0	453	5	3	30	958
Beijing	1,250	1,151	459	937	316	0	6,735
Lanzhou	1,250	0	459	1,040	322	0	6,744
Lhasa	0	0	424	595	7	169	927
Chengdu	1,250	804	459	0	288	0	6,853
Wuhan	0	13,729	459	0	0	0	724
Shanghai	1,250	2,322	459	0	288	0	6,580
Guangzhou	0	10,778	459	0	0	0	725
Kunming	0	6,027	443	139	5	79	801

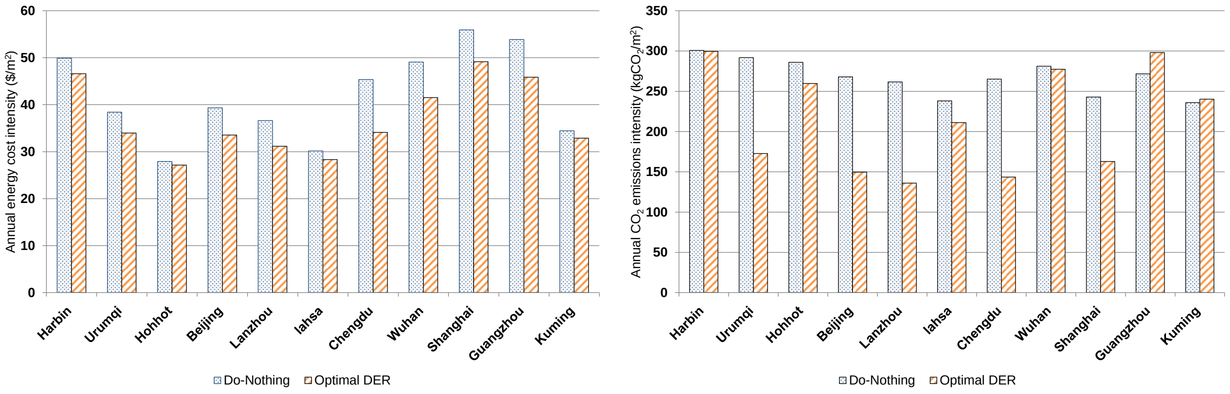


Figure 21 – Energy cost and CO_2 emissions reductions in Chinese commercial buildings through investment in DER (DER-CAM results)

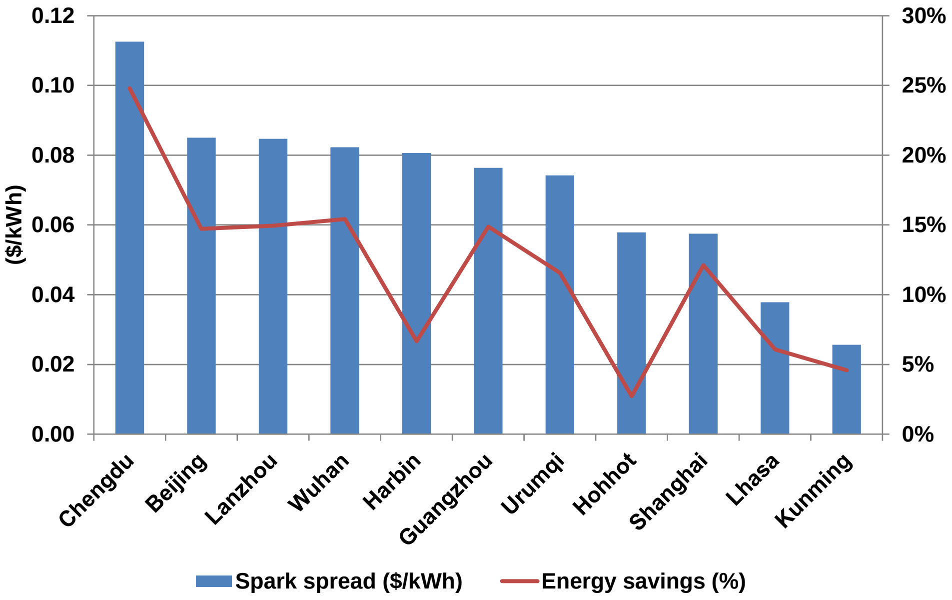


Figure 22 - Spark spread vs. savings analysis for DER adoption in Chinese commercial buildings

3.3. U.S. residential sector results

Table 8 shows DER-CAM economic optimization results for residential buildings in selected U.S. cities. In general, DER's attractiveness is limited and is much less in residential than in commercial buildings. An important reason is that the residential tariffs under consideration are flat. However, DER-CAM has found cost-effective solutions in all cities. Investments are only in solar-enabled technologies, mostly because of the economic competitiveness of solar thermal and PV where electricity prices are high. In the U.S., residential natural gas tariffs, which are generally higher than commercial tariffs, particularly favor the adoption of solar thermal technologies. The largest investments in solar thermal are recommended for buildings located in Atlanta, Minneapolis, and San Francisco. In Miami, the minimal heating needs would not justify such investment. The largest recommended PV investments are in Phoenix, Las Vegas, and San Francisco because of the levels of solar irradiation that those areas enjoy and certainly also because of the higher electricity prices (average of 0.13 $/kWh). The Fairbanks building is the only one for which solar thermal investment is not recommended although PV investments are recommended. Although the performance of PV panels is much lower in this area than in other areas, the electricity rate of about 0.09 $/kWh motivates this investment. Figure 23 shows the cost and CO_2 emissions reductions from adoption of these technologies. Average cost reductions from suggested investments in solar thermal and PV are 4%, with the most significant savings in San Francisco and Atlanta (13% and 10%, respectively). Investment in renewables results in significant emissions reductions: 28% in San Francisco, 21% in Phoenix, and 19% in Las Vegas and Atlanta. The average CO_2 emissions reduction resulting from investments in solar in the whole set of buildings is 11%.

Table 8 – U.S. residential buildings optimal DER technologies

Representative city	CHP (kW)	Electric storage (kWh)	PV (kW)	Heat storage (kWh)	Absorption Chiller (kW)	Solar Thermal (kW)
Albuquerque	0	0	7	0	0	18
Atlanta	0	0	0	0	0	33
Baltimore	0	0	9	0	0	18
Boulder	0	0	0	0	0	12
Chicago	0	0	0	0	0	12
Duluth	0	0	0	0	0	21
Fairbanks	0	0	10	0	0	0
Helena	0	0	0	0	0	16
Houston	0	0	0	0	0	12
Las Vegas	0	0	12	0	0	11
Los Angeles	0	0	2	0	0	14
Miami	0	0	6	0	0	14
Minneapolis	0	0	1	0	0	25
Phoenix	0	0	15	0	0	14
San Francisco	0	0	11	0	0	24
Seattle	0	0	0	0	0	17

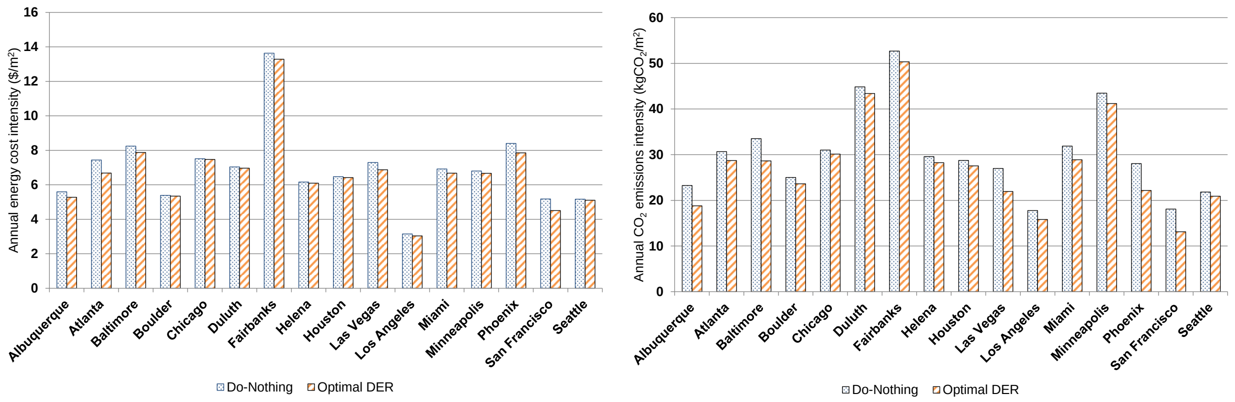


Figure 23 – Energy cost and CO_2 emissions reductions in U.S. residential buildings through investment in DER (DER-CAM results)

3.4. China residential sector results

Table 9 and Figure 21 display the technology mix and intensity reductions results for residential buildings in Chinese cities. Because of China's flat electricity tariffs, only select PV and solar thermal technologies are recommended for residential prototype buildings. Because PV technology is subsidized and electricity prices are higher in China than in the U.S., China's recommended installed solar technology has much larger capacity in buildings than that in the U.S. CHP is not selected for heating because Northern China has district heating systems, and the cost of current coal-fired district heating is relatively cheap compared with making use of waste heat from CHP. The combination of these factors makes CHP generally not attractive in Chinese residential buildings. No solar technology is recommended in Chengdu because of its poor solar radiation. The energy cost reductions achievable by investing in solar technologies are small because of limited roof area for installations. Comparison between Figure 24 and Figure 23 shows that residential buildings in the U.S. are more energy-intensive but significantly less CO_2 emissions-intensive than their Chinese counterparts. For this reason, there is increased potential for environmental improvements from investments in DER technologies in China. The CO_2 emissions reduction in China is 21%, on average and comes mainly from electricity generation by PV panels.

Table 9 – Chinese residential buildings optimal DER technologies

Representative city	CHP (kW)	Electric storage (kWh)	PV (kW)	Heat storage (kWh)	Absorption 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

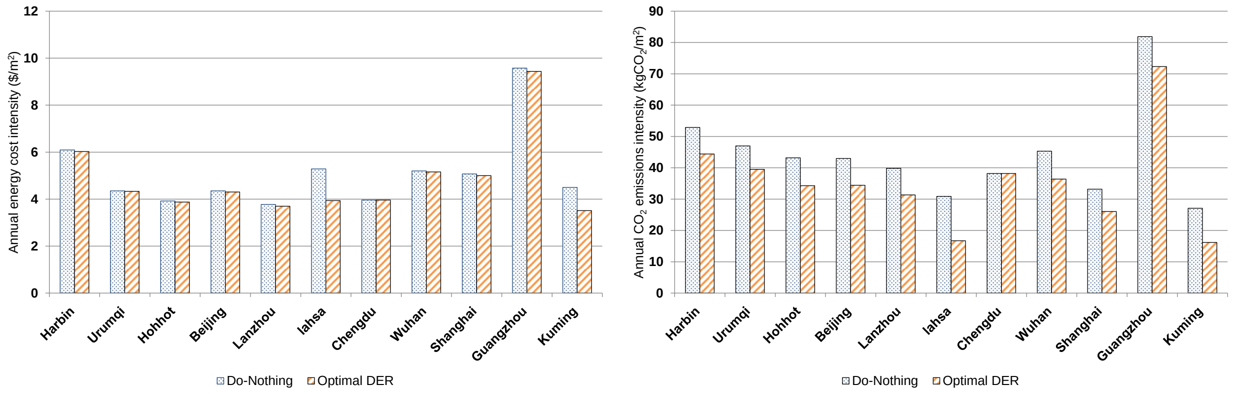


Figure 24 – Energy cost and CO_2 emissions reductions in Chinese residential buildings through investment in DER (DER-CAM results)

3.5. China solar thermal sensitivity analysis in residential buildings

In Kunming, the regression results generate the coefficients for each variable. All variables are significant at the 1% level except solar thermal fixed cost, which is significant at the 5% level. All of the independent variables explain 77.3% of the variation in solar thermal installed capacity. Multiple linear regression results give the coefficients of each independent variable, which to some extent reflect how sensitive the installed capacity of solar thermal is to each of the variables. Figure 25 shows the sensitivity analysis for Kunming.

$$
\begin{aligned}
&InstalledSolarThermalCapacity \\
&\quad = -0.673 * SolarThermalVarCost - 1.825 * HeatStorageCost + 0.053 * PVCost - 1801 \\
&\quad * ElectricityTariff + 1654 * NaturalGasTariff + 0.130 * SolarThermalFixedCost
\end{aligned}
$$

The coefficient for solar thermal variable cost is negative, as anticipated, because the increase in cost will result in a decrease of solar thermal utilization. The coefficient value means that a $10 reduction in variable cost will cause 6.73kW increase in installations in Kunming. The coefficient of heat storage cost is -1.825, which means that solar thermal installations will decrease by 18.25kW when the cost of heat storage increases by $10. The difference in the coefficients doesn't define the variable's significance of impact of on the dependent variable. The heat storage cost coefficient is larger in absolute value than the solar thermal variable cost mainly because the original heat storage cost is $50 while the solar thermal variable cost is $400. A $10 decrease in cost results in a 20% change in heat storage cost but a 2.5% change in solar thermal costs. The PV cost coefficient is positive, as anticipated, because PV competes with solar thermal when the maximum area available for solar technologies becomes a constraint.

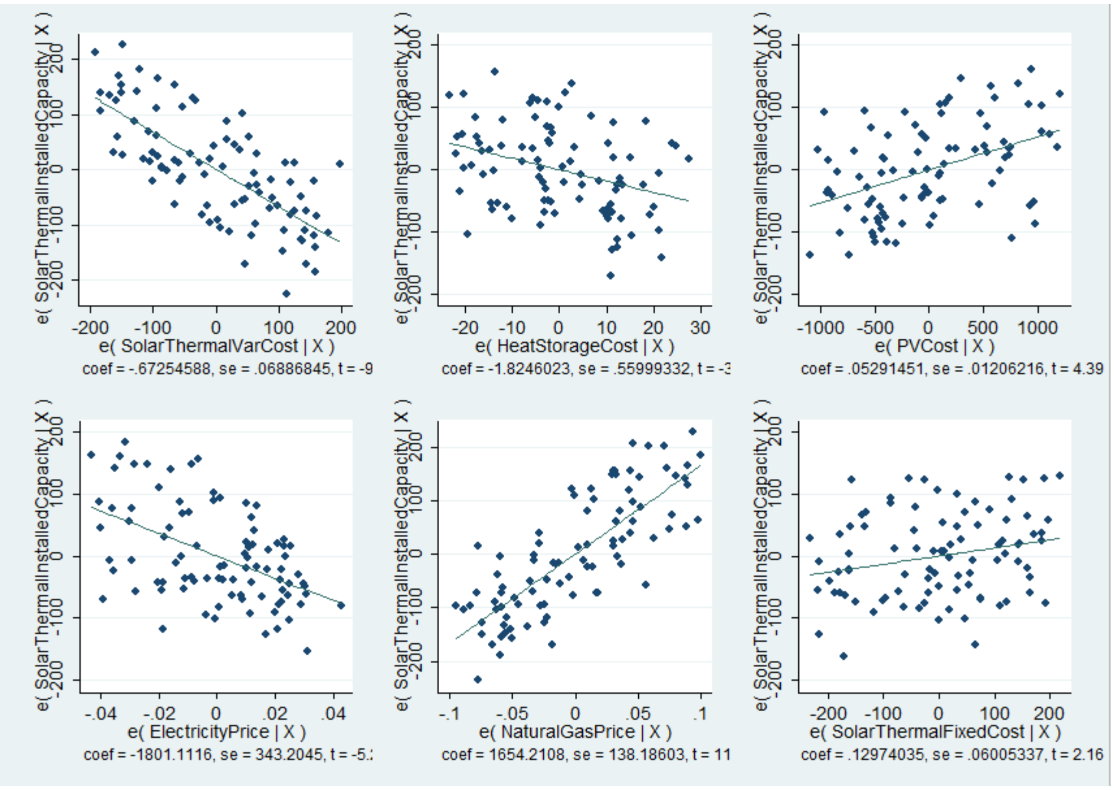


Figure 25 – Sensitivity analysis for Kunming

Stata statistical software shows that each variable linearly impacts the dependent variable of installed solar thermal capacity. It also shows how significant the impacts are. In Kunming, natural gas prices and solar thermal variable cost are the factors that most significantly affect solar thermal installation. Other factors are less significant because they indirectly affect solar thermal installation. For instance, the selection and installed capacity of heat storage technology show a strong correlation with solar thermal installations. Over-production of heat from solar thermal collectors during the day requires a storage medium so that the heat can be used at night. The combined use of solar thermal and heat storage technologies makes the use of solar resources more efficient. Therefore, the sensitivity of installed solar thermal capacity to heat storage cost depends mostly on how strong the correlation is between solar thermal and heat storage installations. In Kunming, the coefficient of PV to solar thermal installation is significant at a 1% level. The significance level of the PV cost coefficient is based on whether the maximum area for solar technologies is reached. The more times this constraint is reached, the more significantly the cost of PV will impact solar thermal installed capacity. Natural gas price has a direct influence on solar thermal installation as solar thermal variable costs because natural gas is the alternative energy option for heating loads. Thus, the significance level of natural gas prices, like solar thermal variable costs, is high in all the cities.

Table 10 shows all multiple linear regressions results.

Table 10 – Solar thermal sensitivity coefficients

	Solar Thermal Variable Cost		**Heat Storage Cost**		**PV cost**		**Electricity**		**Natural Gas**		**Solar Thermal Fixed Cost**		**R Square**
Harbin	-0.905***	0.0866	-1.711***	0.6	-0.012	0.0146	198.48	395.2	4,321.6***	470.6	-0.046	0.081	79.80%
Urumqi	-0.322***	0.072	-0.308	0.482	-0.002	0.007	133.4	149.9	2,052.8***	417.8	0.018	0.031	49.70%
Hohhot	-0.874***	0.0885	-1.658**	0.5443	-0.015	0.0147	181.5	460.3	4,596.5***	493.6	-0.0365	0.08	71.10%
Lanzhou	-0.830***	0.0878	-0.981*	0.503	-0.0032	0.0146	358.4	371.6	3,920.8***	467.1	-0.013	0.075	68.30%
Beijing	-0.884***	0.085	-1.008*	0.552	0.007	0.127	-285.5	344.1	4,794.7***	393.1	-0.028	0.063	77.50%
Shanghai	-0.848***	0.093	-0.618	0.535	0.023*	0.014	-655.7**	275.8	4,025.5***	359.6	0.023	0.071	74.40%
Wuhan	-0.742***	0.84	-1.378**	0.613	-0.0005	0.015	396.2	291.2	2,279.3***	351	-0.1	0.07	64.70%
Chengdu	-0.489***	0.068	-0.828**	0.393	0.0004	0.01	540.9**	221.2	2,408.9***	399.8	-0.079*	0.043	62.20%
Lhasa	-0.384***	0.03	-1.330***	0.22	0.059***	0.006	-1,605.3***	168.3	1,340.6***	73.6	0.064**	0.028	90.10%
Kunming	-0.685***	0.066	-1.854***	0.552	0.052***	0.013	-1,840.9***	343.1	1,699.1***	131.2	0.127**	0.059	77.30%
Guangzhou	-0.615***	0.062	-1.161**	0.473	0.033***	0.009	-964.8***	220.2	2,447.4***	186.7	0.003	0.046	78.30%

In each cell: coefficient / Robust Std. Error

* Significant at the 0.10 level

** Significant at the 0.05 level

*** Significant at the 0.01 level

Comparing the coefficients among different cities gives an idea of the intrinsic characteristics of city loads and solar resources and provides quantitative information for policy makers. For the overall model, more than 70% of the variances of the dependent variable installed capacity for solar thermal are explained by all six independent variables, which is indicated by R square. R square shows the variances of y that are explained by the variables. In the case of Beijing, the model explains 77.5% of the variance in solar thermal installation. The R square reflects how well the model works in each city. The city with the best data performance is Lhasa. Chengdu, Urumqi, Lanzhou and Wuhan are the cities with an R square less than 70%.

Solar thermal variable costs and natural gas prices are statistically significant at the 0.01 level in all the cities because these two factors directly impact solar thermal technology. Solar thermal fixed cost is almost irrelevant in all the cities except for Lhasa and Kunming where there are sufficient solar resources and high natural gas prices. Because the fixed cost is set to be $300 while the variable cost for 1 additional kW is $400, solar thermal fixed cost accounts for only a small portion of total cost; as a result, fixed cost does not significantly affect installed capacity.

3.5.1. Solar thermal variable cost coefficient

The solar thermal variable cost coefficient β_1 in equation (1) is one of the most important factors affecting the attractiveness of installed solar thermal capacity. This variable indicates how much more solar thermal will be installed if the cost of the technology reduces in the future. This variable also gives policy makers quantitative information on which to base incentives for installing solar thermal technology.

The coefficient β_1 is the result of linear regressions. In Beijing and Kunming (Figure 26), the slope of the linear relationship between solar thermal variable cost and solar thermal installed capacity differs; the slope for Beijing is steeper, which means that the dependent variable is more sensitive to cost in Beijing than in Kunming.

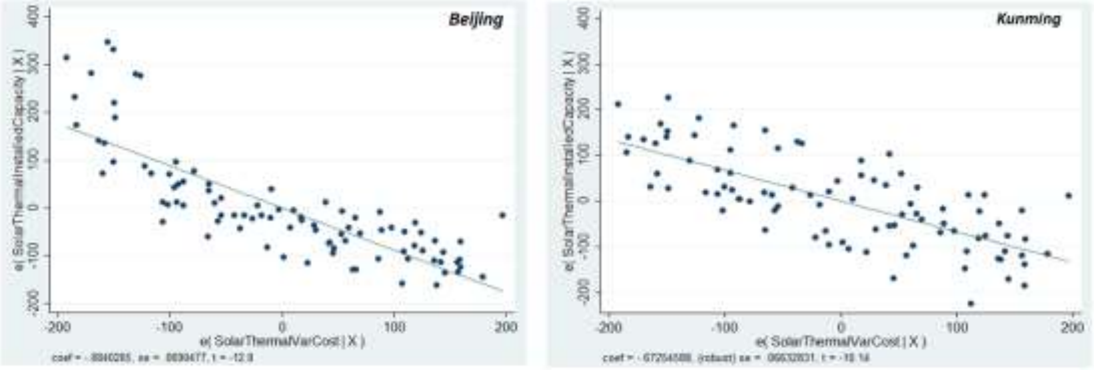


Figure 26 – Linear relationship between solar thermal variable cost and solar thermal installed capacity in Beijing (left) and Kunming (right)

Stata regression results show that Harbin is most sensitive to solar thermal variable cost, which means that a decrease in the cost of the technology will result in the largest sales increase in Harbin among the

Chinese cities studied. The coefficient for five other cities – Wuhan, Beijing, Hohhot, Lanzhou and Shanghai – is approximately 0.8. A subsidy of $10 per kW in these cities will increase an 8kW solar thermal installation in the residential building prototype. Urumqi and Lhasa are least sensitive to solar thermal variable cost. However, the model only explains 49.7% of variances in the case of Urumqi, so the real sensitivity may differ from what this data set indicates. Comparison of coefficients among cities indicates the expected increase in solar thermal installations when technology cost reduces in the future or government subsidies reduce the cost. When costs decrease, Harbin will install more solar thermal technology whereas there will be less change in installed capacity in Lhasa.

Table 11 shows solar thermal variable cost coefficients and space and hot water heating load in seven cities where the R square is more than 70%, considered a sufficient data set. As total heating load (annual space heating and hot water demand) decreases in these cities, the solar thermal variable cost coefficient goes down accordingly because heating energy is a major part of the energy provided by solar thermal technologies. The load profile of residential buildings shows high demand for hot water and space heating compared to the profile in commercial buildings. The city with the highest annual total heating demand, Harbin in this case, is most sensitive to solar thermal technology cost. By contrast, Guangzhou, the city in southern China where heating demand is relatively low, is less sensitive to solar thermal technology cost because heating demand there is small. As a result, even if there is a large reduction in the cost of the technology, solar thermal installations will not be an economically attractive option in Guangzhou. Lhasa, where the heating demand is moderate, is an exception; it has the lowest technology cost coefficient of all the cities studied. This is because Lhasa receives the largest amount of solar radiation of any region in China; solar technologies are very competitive in Tibet, because of the abundant solar resources there (Figure 27).

Figure 27 – Impact of heating load on solar thermal adoption's sensitivity to variable cost

Table 11 – Solar thermal variable cost coefficients and space and hot water heating load in seven Chinese cities

	Harbin	Beijing	Hohhot	Lanzhou	Kunming	Urumqi	Lhasa	Chengdu	Guangzhou	Shanghai	Wuhan
Coefficient	-0.905	-0.884	-0.874	-0.830	-0.673	-0.322	-0.384	-0.489	-0.615	-0.848	-0.842
R square	79.8%	77.5%	71.1%	68.3%	77.3%	49.7%	90.1%	62.3%	78.3%	74.4%	64.7%

In cities with high solar radiation, solar technologies will be attractive no matter the price of the technology. Thus, solar thermal installation will be less sensitive in regions where solar resources are abundant. On the other hand, in the places where there is very low solar radiation, solar technologies will not be selected even when technology cost is very low. As a result, solar thermal installations will not be sensitive to technology cost. Figure 28 ranks solar thermal variable coefficients. In cities such as Lhasa and Guangzhou where solar radiation is the highest and lowest, respectively, β_1 is smaller because the attractiveness or lack of attractiveness of solar thermal technology is largely unaffected by solar thermal technology cost. Sensitivity to technology cost can be approximately explained by the combination of the influences of heating demand and solar radiation level. A city like Harbin, which has modest solar radiation levels and a high heating load, is most sensitive to technology cost. Other elements, including the competitiveness of other technologies, may also affect the sensitivity of solar thermal installations to technology cost.

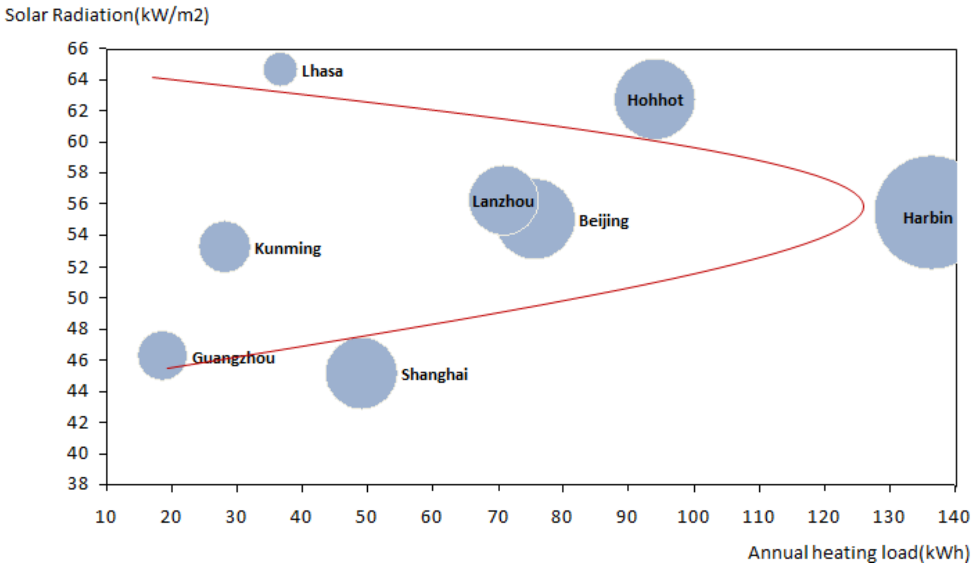


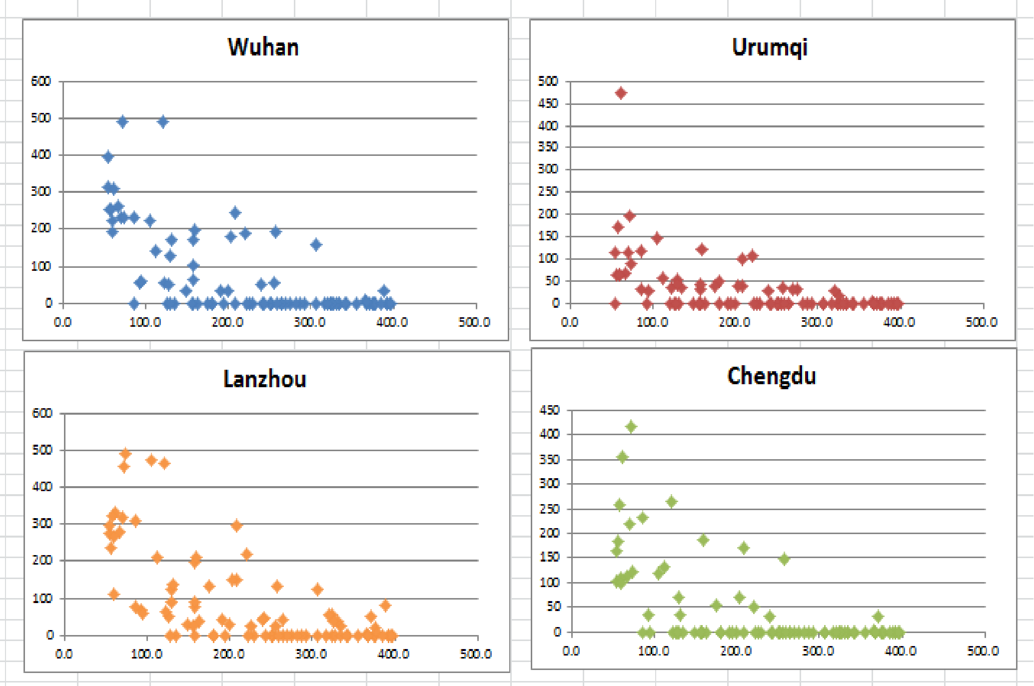
Figure 28 – Impact of heating load and solar radiation on solar thermal's sensitivity to variable cost

For four cities – Lanzhou, Urumqi, Chengdu, and Wuhan – the data from the Stata regression explain less than 70% of the variances of dependent variables. Thus, the β_1 coefficients got from the regression results for these four cities may not explain the true sensitivity of technology cost. For example, in Urumqi, heating demand is relatively high and solar radiation is moderate, so this city should be very sensitive to solar thermal technology cost. However, the regression results tell us that the β_1 coefficient is -0.322, which is even lower than that of Lhasa. In this case, as noted above, the regression model only explains 49.7% of the variances in solar thermal installations (Table 12).

Table 12 – Sensitivity level of solar thermal adoption to variable cost

	Harbin	Beijing	Hohhot	Lanzhou	Kunming	Urumqi	Lhasa	Chengdu	Guangzhou	Shanghai	Wuhan
Coefficient	-0.905	-0.884	-0.874	-0.830	-0.685	-0.322	-0.384	-0.489	-0.615	-0.848	-0.842
R square	79.8%	77.5%	71.1%	68.3%	77.3%	49.7%	90.1%	62.3%	78.3%	74.4%	64.7%

Why does the model work better in some cities than others? A close look at the data for these four cities (Figure 29) gives some insight into why the regression model does not fit them well. For instance, in Lanzhou, if eliminated all the data points for buildings with zero installations, 55 data points remain. Analyzing these 55 data points, it is reached an R square of 73.9%. However, 55 observations are not statistically sufficient for analyzing six variables. The solar thermal variable cost coefficient result changes from -0.830 to -0.854. Or a certain threshold might exist at which the dependent variable becomes sensitive to solar thermal technology cost. In the case of Chengdu, when technology cost is higher than $300, the model shows almost no solar thermal installations.



X: solar thermal variable costs ($)
Y: solar thermal installation (kW)

Figure 29 – Regression data for four Chinese cities

For these four cities, the data sets contain larger numbers of buildings with zero installations than is the case for other cities studied. For example, in Urumqi, there are no solar thermal installations in 55 cases out of a total of 90. The zero installations have a significant impact on the performance of the regression model because one of the assumptions of multiple linear regressions is the linear relationship between the dependent and independent variables. The non-linearity caused by zero installations is the main reason that the regression model doesn't work well in these four cities.

- R square is smaller in these 4 cities (Landzhou, Urumqi, Wuhan, Chengdu) mainly because too many 0 installation of solar thermal increases non-linearity.
- A certain threshold may exist before Y becomes sensitive to X.
- Out of all the cities, Chengdu receives least average solar radiation annually, which means, even with cost reduce, solar thermal technologies won't be sufficiently competitive simply because of short of solar radiation.
- Annual solar radiation is in average level in Wuhan and Urumqi, but both cities receive less sunlight in winter time when heating demand is higher.
- Based on current price (400$), directly subsidy on solar thermal cost may not see large increase of installation quickly in these 4 cities.

3.5.2. Natural Gas Prices

In the regression results for all cities, natural gas prices have a strong impact on the adoption of solar thermal technology because natural gas is the alternative fuel choice for heating loads (Figure 30). In general, where natural gas prices are high, solar thermal technology installations will be attractive. In cities where natural gas prices are lower, customers are less likely to install solar thermal water heaters or other solar thermal technologies because these installations may not be an economical investments. However, the sensitivity of natural gas prices to solar thermal installed capacity is a key value in analyzing the impact on the solar thermal market of a change in natural gas prices. When natural gas prices increase, a more optimistic solar thermal market forecast can be expected. However, the same size increase in natural gas prices can have different outcomes in different regions because some regions are more sensitive to natural gas price changes than others. Regions with cold winters and high heating demand will be more sensitive to natural gas prices. The natural gas set point price is also a key factor in the sensitivity analyses. In cities where the natural gas price is already very high, like Kunming, a small increase might not have much effect on whether customers choose to install solar thermal technology.

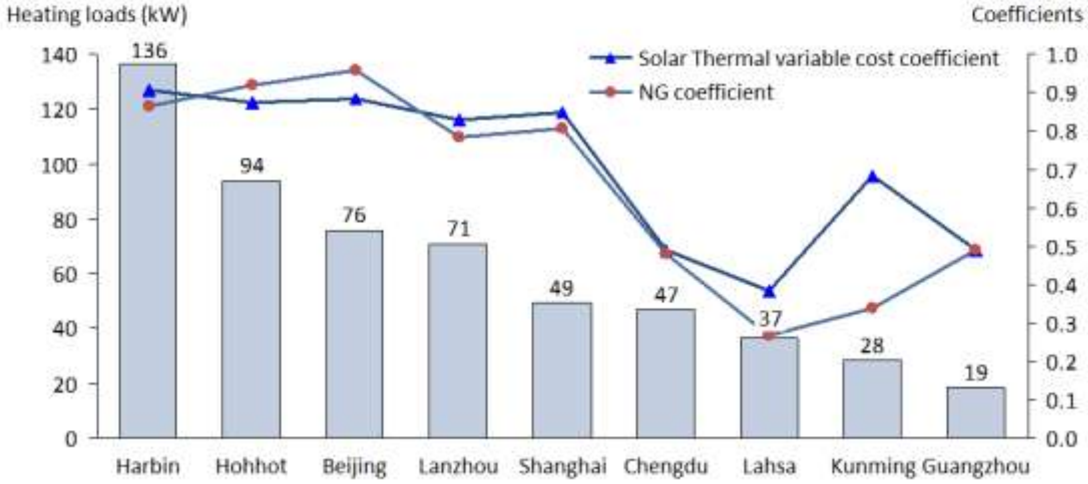


Figure 30 – Impact of heating load on solar thermal adoption's sensitivity to variable cost and natural gas price

3.5.3. Heat Storage Cost

Heat storage technology acts as a reservoir for heat when there is redundant generation and releases heat when demand is high. Because solar thermal technologies only generate heat during the day when the collectors receive solar radiation, these technologies cannot meet evening and nighttime demand. The efficiency of solar thermal technologies also changes during the day according to temperature and the availability of solar resources. Thus, the time at which solar thermal technology produces peak heating likely does not match the time of peak heating demand. Most solar thermal water heater products on the market are designed with a heat storage tank for accumulating hot water during the day for use in the evening or early the next morning. The efficiency of the heat storage tanks is a key element of the total efficiency of a solar thermal water heater. Because of the timing of heat production by solar technologies, combining them with heat storage is a very important option, and a strong correlation between installation of solar thermal technology and of heat storage is expected. When solar thermal technology generates a large amount of heat, it is more efficient to use storage to keep the heat for use when demand is high. In seven cities out of 11 in the regression results, heat storage cost has a significant impact on the attractiveness of solar thermal installations (Table 13). The correlation between installations of heat storage and solar thermal technologies implies that heat storage cost will have an impact on solar thermal installation. With lower heat storage cost, more solar thermal will be installed. Thus, the heat storage coefficient is anticipated to be negative.

Table 13 – Solar thermal sensitivity coefficients to heat storage variable cost

	Guangzhou	Chengdu	Kunming	Hohhot	Lhasa	Harbin	Wuhan
Heat Storage	-1.161** 0.473	-0.828** 0.393	-1.854*** 0.552	-1.658** 0.5443	-1.330*** 0.220	-1.711*** 0.600	-1.378** 0.613

The correlations between solar thermal and heat storage installations can be seen in data generated from large-volume DER-CAM runs. In almost all the cities, there is a positive linear relation between solar thermal installed capacity and heat storage installed capacity. Figure 31 shows an example of this correlation for the city of Kunming.

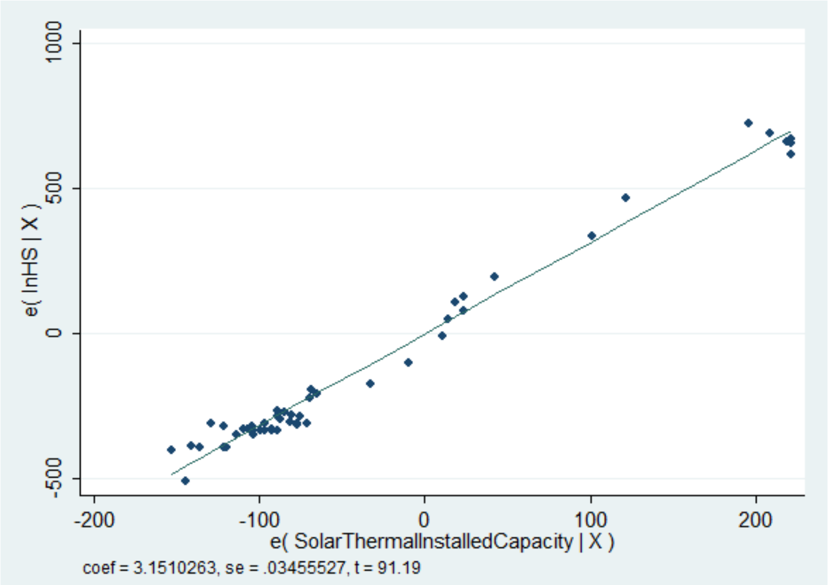


Figure 31 – The correlation between installed heat storage capacity and installed solar thermal capacity in Kunming

The effect of heat storage costs on solar thermal installed capacity depends heavily on how strong the correlation is between heat storage installation and solar thermal installation. In Kunming, the correlation is stronger than in Guangzhou, as shown in Figure 32. As a result, the heat storage cost coefficient in Kunming is higher (in absolute value) than that in Guangzhou. The solar thermal installed capacity is more sensitive to heat storage technology cost in Kunming than Guangzhou, which means that a change in heat storage cost will make a bigger difference in solar thermal installed capacity in Kunming. Moreover, a reduction in the cost of heat storage may boost the utilization of solar thermal technologies because of the correlation, and vice visa. In the regions where the correlation is stronger, it is possible that incentives for heat storage technology will boost the utilization of solar thermal technology as well.

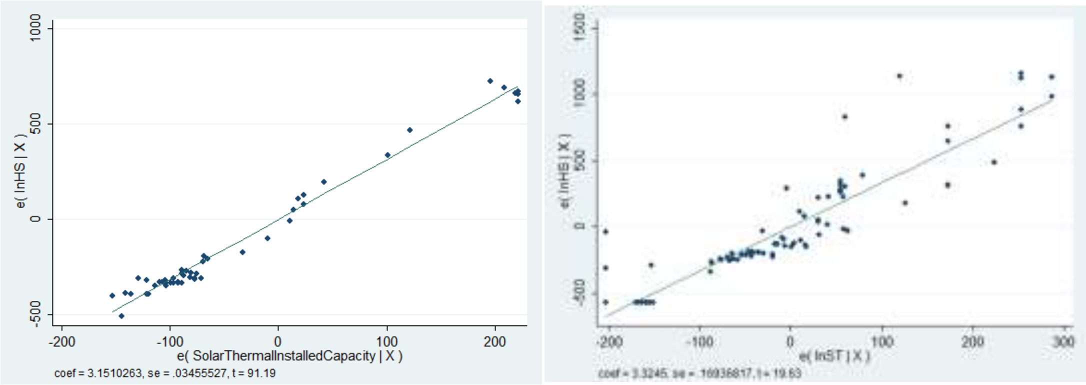


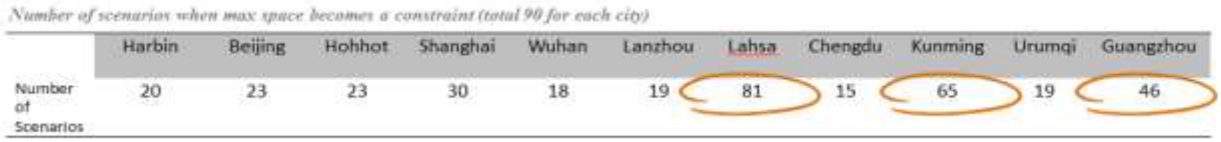
Figure 32 – Correlation between solar thermal and heat storage installations in Kunming (left) and Guangzhou (right)

3.5.4. PV vs. Solar Thermal

PV and solar thermal technologies both convert solar energy into other useable forms. PV technology converts solar resources to electricity, and solar thermal technology converts solar energy to heat. Electricity generated by PV will feed electrical-only demands as well as demands like cooling (i.e., via a traditional electric air conditioner), space heating (via electric heating devices), and water heating. Heat generated by solar thermal technologies can be used for space heating and water heating. It can also be used in absorption chillers to meet cooling demand. Because both technologies use solar resources as input, they will likely be used more heavily in regions with large amounts of solar radiation. Each building prototype has a limited area where solar collectors can be installed, so these two solar technologies might compete for this limited space. Thus, a policy of encouraging one technology might discourage the other because of space limitations.

In this research, it is found that in three cities – Lhasa, Kunming, and Guangzhou – there is significant competition between PV and solar thermal. Table 14 shows the number of scenarios in which the maximum space for both PV and solar thermal (700 m^2) is reached. In 81 out of 90 cases in Lhasa, all available space for solar technologies is occupied.

Table 14 – Number of cases in which the maximum space for solar technologies is used



Number of scenarios when max space becomes a constraint (total 90 for each city)

	Harbin	Beijing	Hohhot	Shanghai	Wuhan	Lanzhou	Lahsa	Chengdu	Kunming	Urumqi	Guangzhou
Number of Scenarios	20	23	23	30	18	19	81	15	65	19	46

The competitiveness of PV and solar thermal differs in the three cities. When lack of roof area becomes a constraint (i.e., the maximum, 700 m^2, is used), Kunming will see more PV installations (200-400) than Lhasa (100-300) (Figure 33). PV is more competitive in Guangzhou because heating demand there is lower.

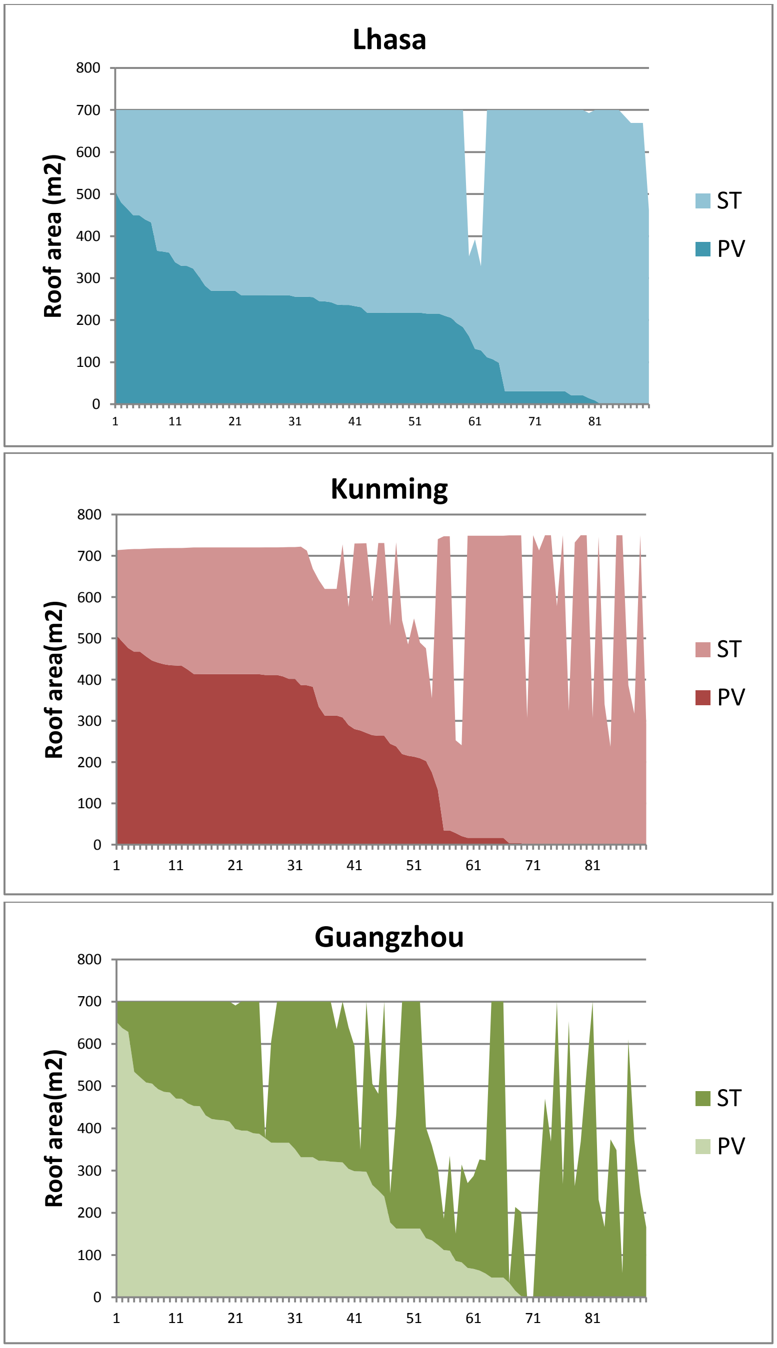


Figure 33 – Roof area constraints on solar thermal and PV technology installation in four Chinese cities

4. Summary and Conclusions

This study analyzed the economic and environmental viability of DER in prototype buildings in selected U.S. (year 2020-2025 projection) and Chinese cities, with special in-depth examination of solar thermal technologies in China.

In U.S. commercial buildings, energy costs were reduced by 17% as a result of the optimal DER investments modeled by the DER-CAM software. In Chinese buildings, energy costs were reduced by 12%.

If technology characteristics are fixed, the structure and prices of electricity tariffs as well as the cost of natural gas are the most important factors determining whether DER is likely to be adopted; these factors have a stronger influence on the attractiveness of DER than does climate.

This study found that DER are potentially competitive in both warmer and colder climates. TOU tariffs, especially TOU demand charges, make DER more attractive. Very high electricity prices can stimulate DER adoption even without TOU rates.

CHP is not attractive in cities with higher natural gas prices; other DER technologies are more cost effective in this situation. The attractiveness of absorption cooling is limited by the availability of CHP and solar thermal. For both the U.S. and China, high spark spreads normally increase the economic attractiveness of DER.

In warmer climates with conducive electricity tariff structures, PV can be purchased economically, and CHP has the potential provide cooling through absorption systems. In cold areas, CHP can cost-effectively meet electrical and heating needs. Battery storage may in some cases be needed to balance mismatches between building energy loads and solar production. The economics of DER are shown to be on average more attractive in warmer areas.

In general, DER technologies are revealed to be better investments in commercial buildings than in residential buildings from both economic and CO_2 emissions reduction perspectives. The main reason for this is the difference between commercial and residential electricity tariff structures and the energy load profiles of these two types of buildings. Both the American and Chinese residential flat tariffs are generally not conducive to adoption of CHP and storage technologies; however, higher electricity prices can stimulate investments in solar PV. Solar thermal is also largely attractive in the residential context. In Northern China, the price of coal-fired district residential heating makes CHP systems not cost effective.

The results of this study show the importance of DER for abating CO_2 emissions. In the U.S., the average emissions reduction in commercial buildings from adoption of DER is 19%, mostly as a result of significant investments in PV. In China, the average emissions reduction is 20%, and investment in CHP systems is the main contributor to this reduction. When there are significant investments in electrical storage, the decline in emissions will likely be smaller because of the electricity used to charge the batteries.

From the point of view of technology, internal combustion engines are the preferable prime mover for CHP because they are more economic than micro-turbines but with similar efficiencies and heat-to-power ratios, and they are much cheaper than fuel cells. In China, government subsidies have proven effective in promoting adoption of PV and storage technologies, without which it is found that these technologies were not cost-effective in both retail and residential buildings. Other policies, such as low natural gas prices, can also significantly affect the economics of CHP systems, especially in climates where these systems are most attractive.

For solar thermal technology in Chinese residential buildings, the northern and eastern parts of China are more sensitive to changes in the cost of the technology. That is, if technology costs decrease in the future, residents living in these regions will be likely to adopt more solar thermal systems than those living in other regions. The southern part of China is less sensitive to technology cost. Cities like Lhasa on the Tibetan Plateau and Chengdu in the Sichuan Basin exhibit the least sensitivity to solar thermal technology costs.

Factors that may positively or negatively affect the procurement of solar thermal systems are:

- Large domestic hot water and space heating loads
- Abundant solar resources
- High cost of back-up energy
- Availability of area for collectors

Regression coefficients give us quantitative indicators of what will happen if technology costs decrease. In certain cities, reducing solar thermal variable cost yields promising increase of solar thermal adoption. However, the sensitivity of solar thermal adoption to its variable cost varies with building’s heating load and cities solar radiation.

Solar thermal technologies compete with PV technologies in regions where prices of back-up fuels like natural gas are higher. In Guangdong, Yunnan, and Tibet provinces, more competition exists between these two types of solar systems if technology costs reduce or natural gas prices increase. Heat storage is the complementary technology because the combined use of solar thermal and heat storage technologies makes it possible to save the solar energy generated in the daytime for use during the evening when demand is high. Therefore, an increase in installations of one technology will boost customers’ investments in the other.

Subsidies to encourage investment in solar thermal technologies should be attributed to regions sensitive to technology cost. Incentive policies, such as providing to investors a fixed amount of subsidy for each kW installed, is more effective in northern China. Prices of conventional fuels like natural gas will play an important role in customers’ investment decisions. Higher natural gas prices are indirect incentives to residents to switch to solar thermal. The relationships among different distributed technologies must be considered when making policies. For example, giving incentives to both solar thermal and PV might not be effective because these two solar technologies compete for the same space, and the availability of space will limit the maximum number of solar collectors that can be installed.

Acknowledgments

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