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ABSTRACT

The following paper conducts a regional analysis of the U.S. and Chinese buildings' potential for adopting Distributed Energy Resources (DER). The expected economics of DER in 2020-2025 is modeled for a commercial and a multi-family residential building in different climate zones. The optimal building energy economic performance is calculated using the Distributed Energy Resources Customer Adoption Model (DER-CAM) which minimizes building energy costs for a typical reference year of operation. Several DER such as combined heat and power (CHP) units, photovoltaics, and battery storage are considered. The results indicate DER have economic and environmental competitiveness potential, especially for commercial buildings in hot and cold climates of both countries. In the U.S., the average expected energy cost savings in commercial buildings from DER-CAM's suggested investments is 17%, while in Chinese buildings is 12%. The electricity tariffs structure and prices along with the cost of natural gas, represent important factors in determining adoption of DER, more so than climate. High energy pricing spark spreads lead to increased economic attractiveness of DER. The average emissions reduction in

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commercial buildings is 19% in the U.S. as a result of significant investments in PV, whereas in China, it is 20% and driven by investments in CHP.

Keywords: Building Modeling and Simulation, Distributed Energy Resources (DER), Energy Efficiency, Combined Heat and Power (CHP), CO_2 emissions

1. Introduction

The transition from a centralized and fossil-based energy paradigm towards the decentralization of energy supply and distribution has been a major subject of research over the past two decades. Various concerns have brought the traditional model into question; namely its environmental footprint, its structural inflexibility and inefficiency, and more recently, its inability to maintain acceptable reliability of supply. Under such a troubled setting, distributed energy resources (DER) comprising of small, modular, electrical renewable or fossil-based electricity generation units placed at or near the point of energy consumption, has gained much attention as a viable alternative or addition to the current energy system.

In 2010, China consumed about 30% of its primary energy in the buildings sector, leading the country to pay great attention to DER development and its applications in buildings. During the 11th Five Year Plan[2] (FYP), China has implemented 371 renewable energy building demonstration projects, and 210 photovoltaics (PV) building integration projects. At the end of the 12th FYP, China is targeting renewable energy to provide 10% of total building energy, and to save 30 metric tons of CO_2 equivalents (mtce) of energy with building integrated renewables. China is also planning to implement one thousand natural gas-based distributed cogeneration

[2]China's 11th FYP is from 2006 to 2011.

demonstration projects with energy utilization rates over 70% in the 12^{th} FYP. All these policy targets require significant DER systems development for building applications. China's fast urbanization makes building energy efficiency a crucial economic issue; however, only limited studies have been done that examine how to design and select suitable building energy technologies in its different regions.

In the U.S., buildings consumed 40% of the total primary energy in 2010 [1] and it is estimated that about 14 billion m^2 of floor space of the existing building stock will be remodeled over the next 30 years. Most building's renovation work has been on building envelope, lighting and HVAC systems. Although interest has emerged, less attention is being paid to DER for buildings. This context has created opportunities for research, development and progressive deployment of DER, due to its potential to combine the production of power and heat (CHP) near the point of consumption and delivering multiple benefits to customers, such as cost savings, increased energy security, environmental improvements, market competition, innovation, and active engagement by consumers. Prevailing DER technologies include CHP-ready reciprocating engines (ICE), microturbines (MT), fuel cells (FC) and various renewable sources, such as PV panels.

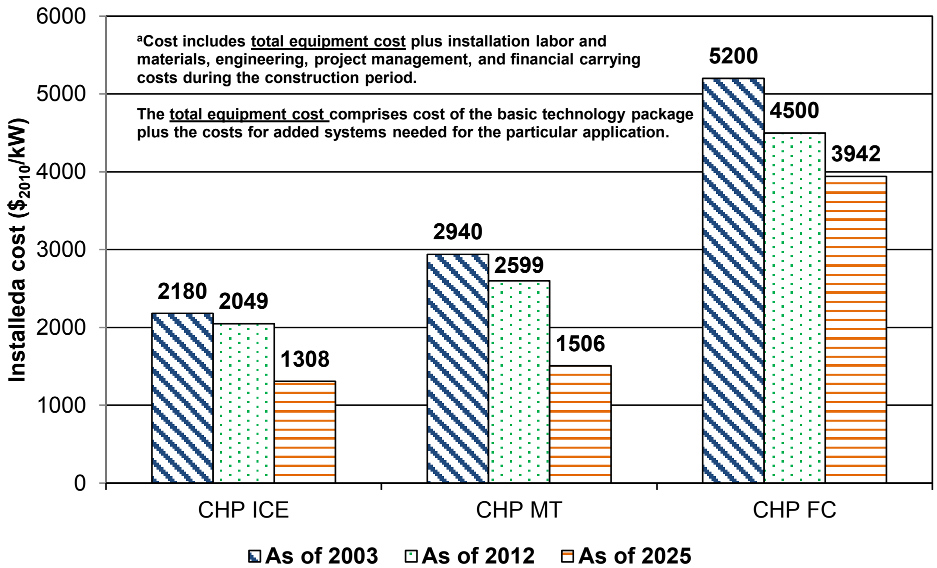


Figure 1 – Evolution of the installed costs of medium-sized CHP internal combustion engines (ICE), microturbines (MT) and fuel cells (FC) over the last decade, and forecast of prices for 2025 [2,3,4].

Due to an increased focus on R&D and widespread pilot project validation, the installed costs of DER have been going down significantly during the last decade. Figure 1 shows this trend, based on past estimates and on Energy Information Administration's (EIA's) price forecast for 2025. Additionally, as a result of technological advances in exploration and production of natural gas, gas prices have been going down, making it an increasingly attractive and affordable energy source for the commercial and residential sectors, where electricity use still dominates [5]. Most DER units that operate on natural gas are able to capture and utilize waste heat from electricity generation, increasing its potential penetration in buildings.

Currently, the common approaches to evaluating an individual technology's potential for building energy efficiency impacted by on-site generation are ineffective and rarely find the global optimum. To tackle climate change, government policies often promote clean technologies, such as PV or FC, and provide incentives for their adoption irrespective of how the technologies are applied. In both China and the U.S., the current strategy for promoting ultra-low energy buildings relies heavily on dispersed renewable technologies combined with (by current standards) extreme efficiency measures. The cost effectiveness and energy saving potential from these technologies are highly sensitive to building energy services requirements, usage patterns, tariffs, and incentives. To holistically achieve the most cost or carbon effective building energy efficiency and on-site generation combination, multiple technology options and their operating schedules need to be optimized simultaneously in order to choose the best technology combination for a particular building.

DER adoption modeling requires the following inputs: the building's end-use energy load profile, the city's solar radiation data, the local electricity and natural gas tariffs, and the performance and cost of available technologies. The methodology and key assumptions followed are addressed in the next section.

2. Methodology

The Distributed Energy Resources Customer Adoption Model (DER-CAM) optimization tool has been used in this study. DER-CAM has been in development by Lawrence Berkeley National Lab (LBNL) for over 10 years, and has been widely used to assess DER alternatives, to find optimal results, and for energy-economic assessments [6,7,8]. Figure 2 shows the energy flows modeled by DER-CAM.

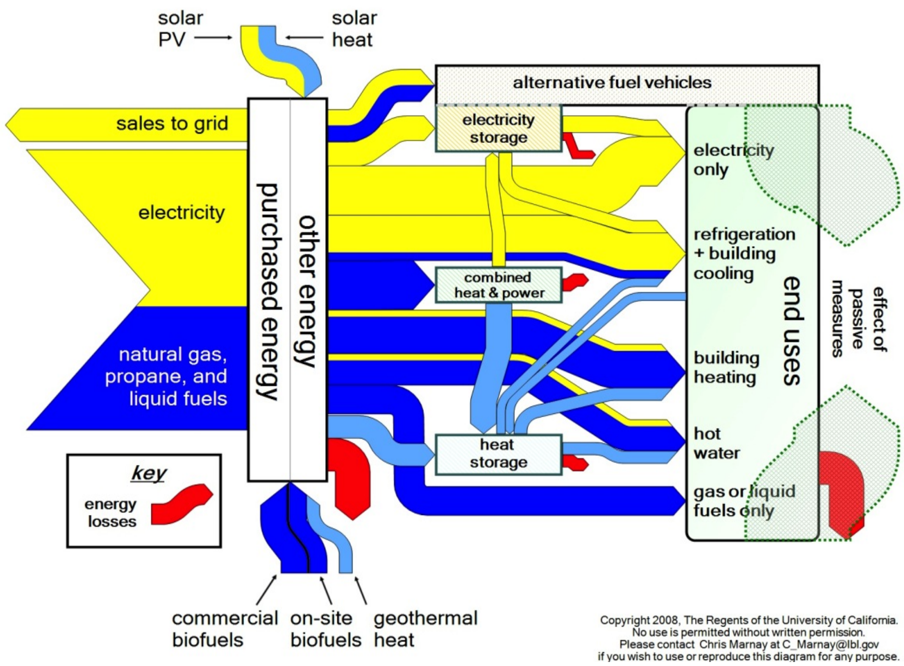


Figure 2 – Input/Output representation of DER-CAM optimization, given building energy service requirements to the right and the available energy sources to the left.

DER-CAM finds optimal supply technology combination and its operating schedules. The tool can solve the entire building energy system holistically, simultaneously, and in a technology-neutral manner; that is, such that the cost, energy use, carbon, other metrics, or combination of metrics is minimized, while all technology opportunities for service provision are equally considered and equitably traded off against each other.

In this study, 16 representative American cities are selected for DER system analysis. Each city is representative of one of the 16 widely used U.S. climate zones, developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Figure 3 shows the ASHRAE climate zone map and Table 1 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.

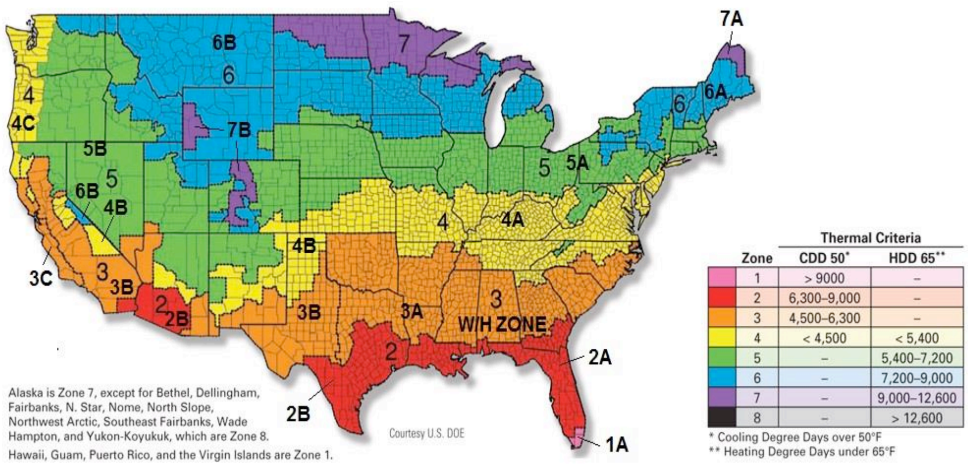


Figure 3 – ASHRAE U.S. Climate zones and respective thermal criteria (Adapted from [9]).

Table 1 – U.S. Representative cities, their corresponding Climate zones and country population weight factor (Adapted from [9]).

Representative city	State	Climate Zone	Weight factor for the 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

Due to the large size and diversity of the U.S., there are dramatic climate variations between different regions of the country. At the same time, average hourly temperatures of the day for each month of the year vary widely across different cities. As an example, Fairbanks exhibits stable temperatures throughout any day of the year, with very cold winters, fairly warm summers and a yearly average under -1ºC. However, in Las Vegas there is much higher temperature variability during the day, and values rarely fall under -5ºC but can reach close to 30ºC in the summer. Thus, Fairbanks experiences a wide range of temperatures over the year, whereas Las Vegas is more likely to have a wide daily range. Similarly, 11 representative Chinese cities [10] – Harbin, Urumqi, Hohhot, Lanzhou, Beijing, Lhasa, Shanghai, Wuhan, Chengdu, Guangzhou, and Kunming were selected. Figure 4 shows the climate zone map used to select the cities.

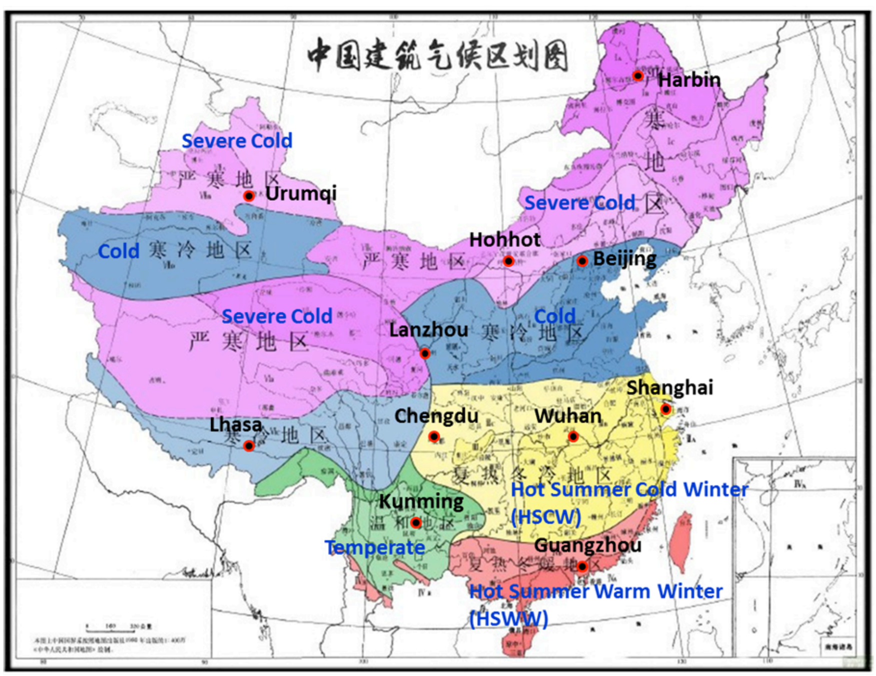


Figure 4 – China's climate zones and the selected cities [10].

Average hourly diurnal temperatures for each month can differ from city to city. For example, while Harbin is located in inland China, Shanghai is in a coastal area. Both cities show strong temperature variability during any 24 hours irrespective of season; however this is less evident in Shanghai due to maritime climate influence. Harbin is the coldest city in the selected group with a yearly average temperature of 4ºC while in Shanghai, this value is 17ºC. In Harbin, temperatures fall as low as -29ºC but in the summer, they exceed over 30ºC. In the case of Shanghai, summer temperatures can reach as high as 37ºC but in the winters they can fall to -5ºC.

2.1 Building type selection

In order to understand building energy performance in different climate zones, two prototype buildings were modeled for chosen cities of each country. The American commercial buildings are part of the compiled U.S. Department of Energy (DOE) commercial reference buildings model set [11, 12], and correspond to a 46 320m^2 12-floor large office with one basement floor, and a 4-floor medium-rise multi-family residential complex.

The Chinese buildings were a 7-floor 36 000m^2 shopping center (retail) with two basement floors, and a 10-floor high-rise multi-family building [10,13]. The commercial building prototype has been developed by an on-site survey and literature review and modeled in compliance with China's Ministry of Housing and Urban-Rural Development (MOHURD) commercial building energy efficiency standard GB50189-2005 [14]. The residential prototype building is developed based on U.S. DOE multi-family apartment prototype building, as well as

Chinese studies in compliance with China's residential building energy efficiency standards. The detailed prototype building characteristics for climate zones are described in [10].

2.2 Building loads

In order to estimate the economic performance of DER technologies, it is important to know the buildings' end-use energy load profiles. For both the U.S. and China, the annual energy performance of the commercial and residential prototype buildings was simulated in EnergyPlus [15]. The commercial and residential energy usage intensities, for both countries, are shown as site energy in figures 5 and 6. The cities are ordered from coldest to hottest.

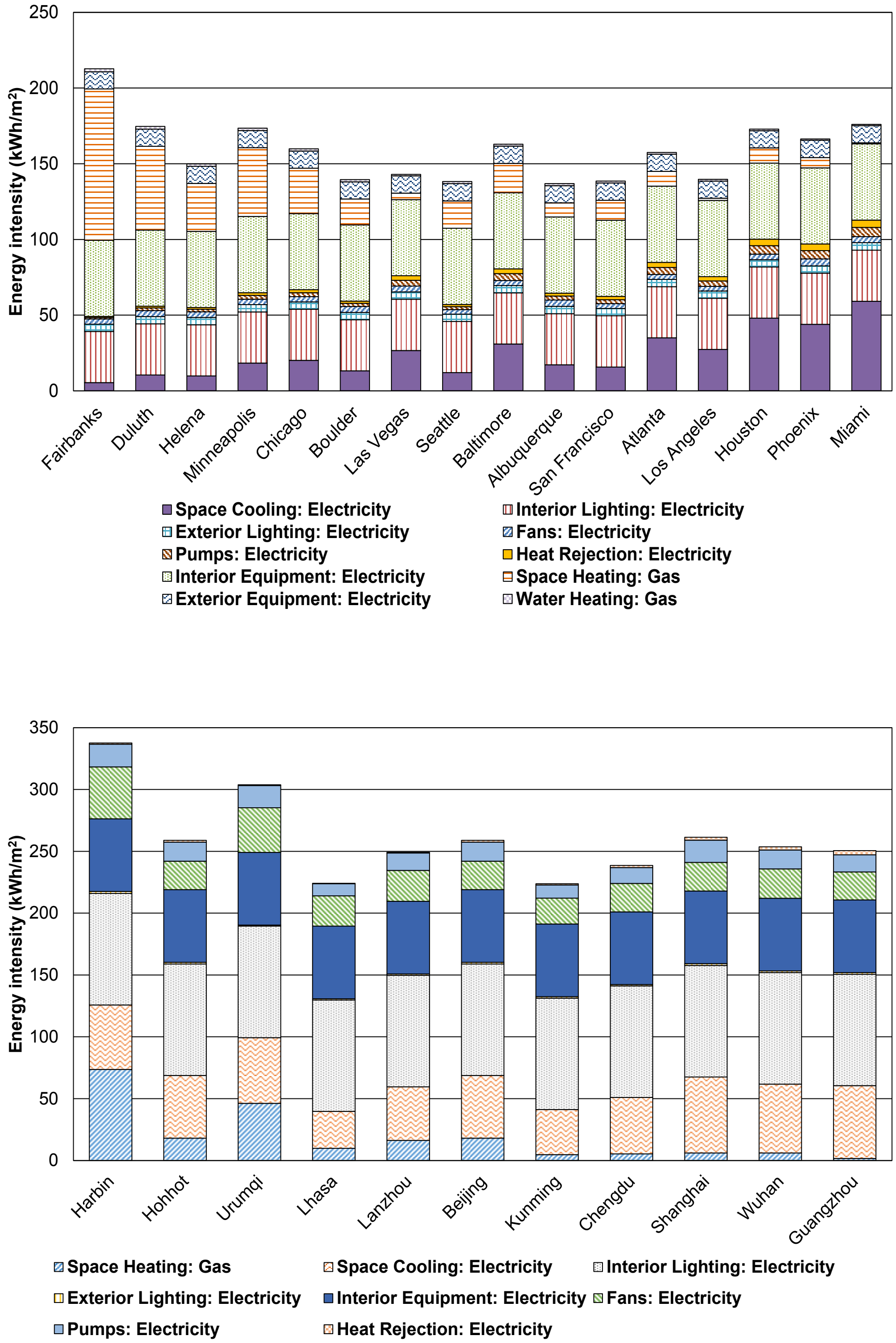


Figure 5 - Annual energy usage intensity of office complexes in representative cities of the U.S. and shopping malls in Chinese representative cities.

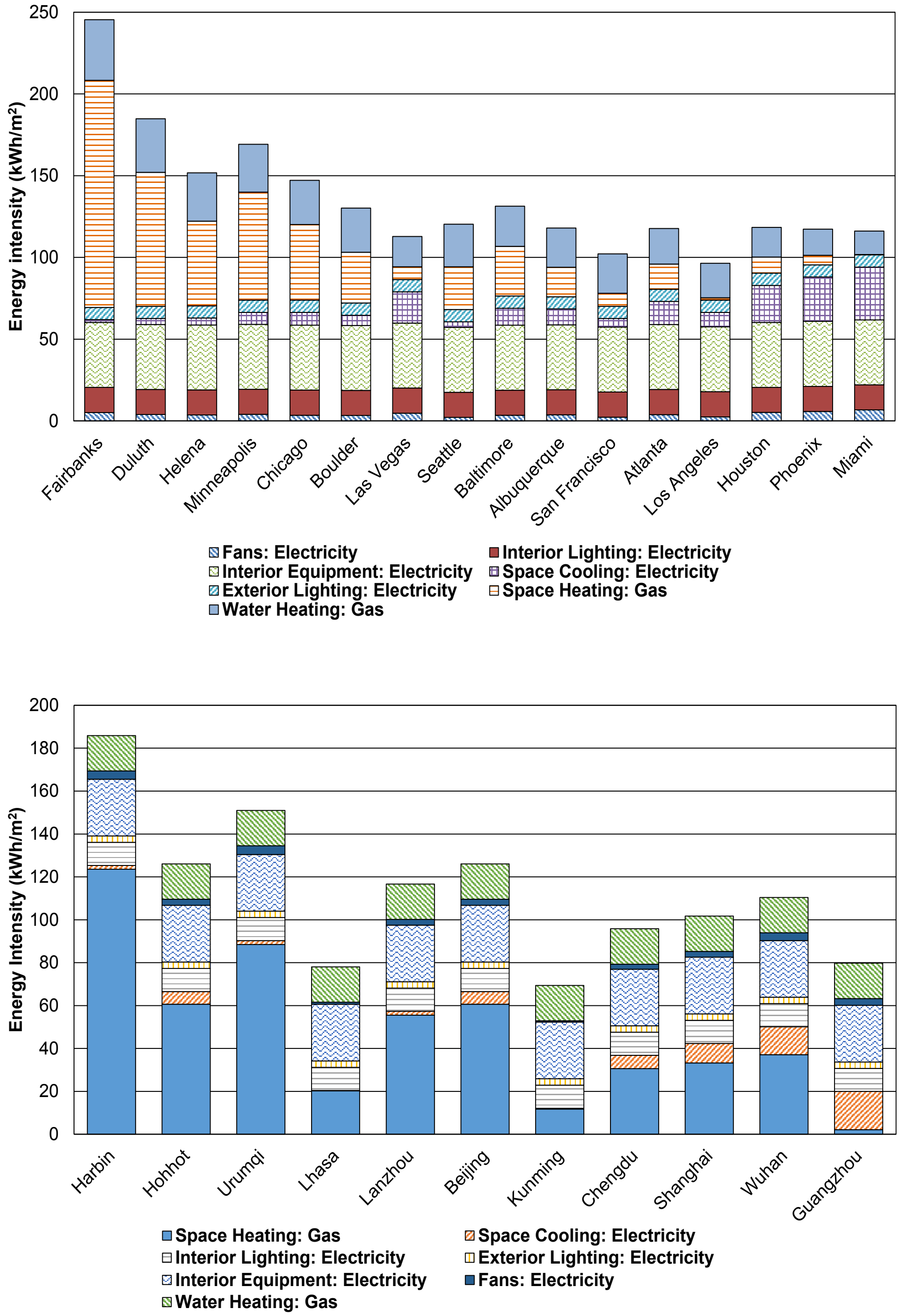


Figure 6 – Annual energy usage intensity of residential buildings in the U.S. and Chinese representative cities.

One can notice, for both the U.S. and Chinese cases, that the commercial prototype buildings are dominated by internal loads, of which lighting and internal equipment together consume the majority of the building's energy. In the China case, the selected prototype building is a shopping mall with large internal loads. The buildings use more energy on cooling than heating in most climate zones, resulting in no sensitivity to climatic impacts. On the other hand, a reasonable number of office buildings in northern, colder areas of the U.S., consume more energy on heating than cooling. Invariably, the residential buildings' internal loads are lighter than the office buildings', and thus more sensitive to climate, as figures 5 and 6 show.

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

Figure 5 shows that retail building in China is drastically more energy-intensive than the U.S. large office building. On average, the Chinese retail building annual energy use intensity (EUI) is 245kWh/m^2, whereas U.S. office buildings use only 159kWh/m^2. In the cold Harbin climate, the EUI of the retail building goes over 337kWh/m^2 while in the coldest location in the U.S., Fairbanks, it is under the 250kWh/m^2. On the residential side, Figure 6 shows that U.S. households spend in average 136kWh/m^2 against around 113kWh/m^2 in China. In Fairbanks the energy intensity can reach 250kWh/m^2, while in Harbin only 182kWh/m^2. The EUI difference between the two countries is mainly driven by occupant behavior, which influences the lighting and appliances energy usage, even though the U.S. building codes are more stringent than Chinese ones.

2.3 PV System Performance

To evaluate solar radiation and its impact on PV systems, the PVWatts online platform is used [16]. Figure 7 shows crystalline silicon PV performance in selected U.S. and Chinese cities. As formatted in PVWatts, the buildings' PV systems are assumed mounted at a fixed title angle equivalent to their cities latitude with fixed South azimuth orientation. The results are obtained based on PV system AC rating of 1kW, with an overall derate factor 0.77[3], this giving a DC rating of approximately 1.3kW and PV system approximate area of 11.4 m^2. The data is obtained by averaging PV system hourly AC output power on an annual basis.

One clear observation from Figure 7 is that the PV system performance can vary significantly from one region to another and this affects the economics of PV. Albuquerque, Las Vegas, and Phoenix enjoy high rates of solar irradiation and higher potential PV performance. Chinese cities with similar levels of irradiation are Hohhot and Lhasa, however, since China has only one time zone, PV peak production time differs across regions. Figure 7 also indicates that the range of PV performance is slightly higher across U.S. cities, from 0.5kW to 0.9kW of hourly peak power generated.

[3] The overall derate factor is calculated by multiplying a couple of component derate factors such as inverter and transformer, AC and DC wiring, soiling and age.

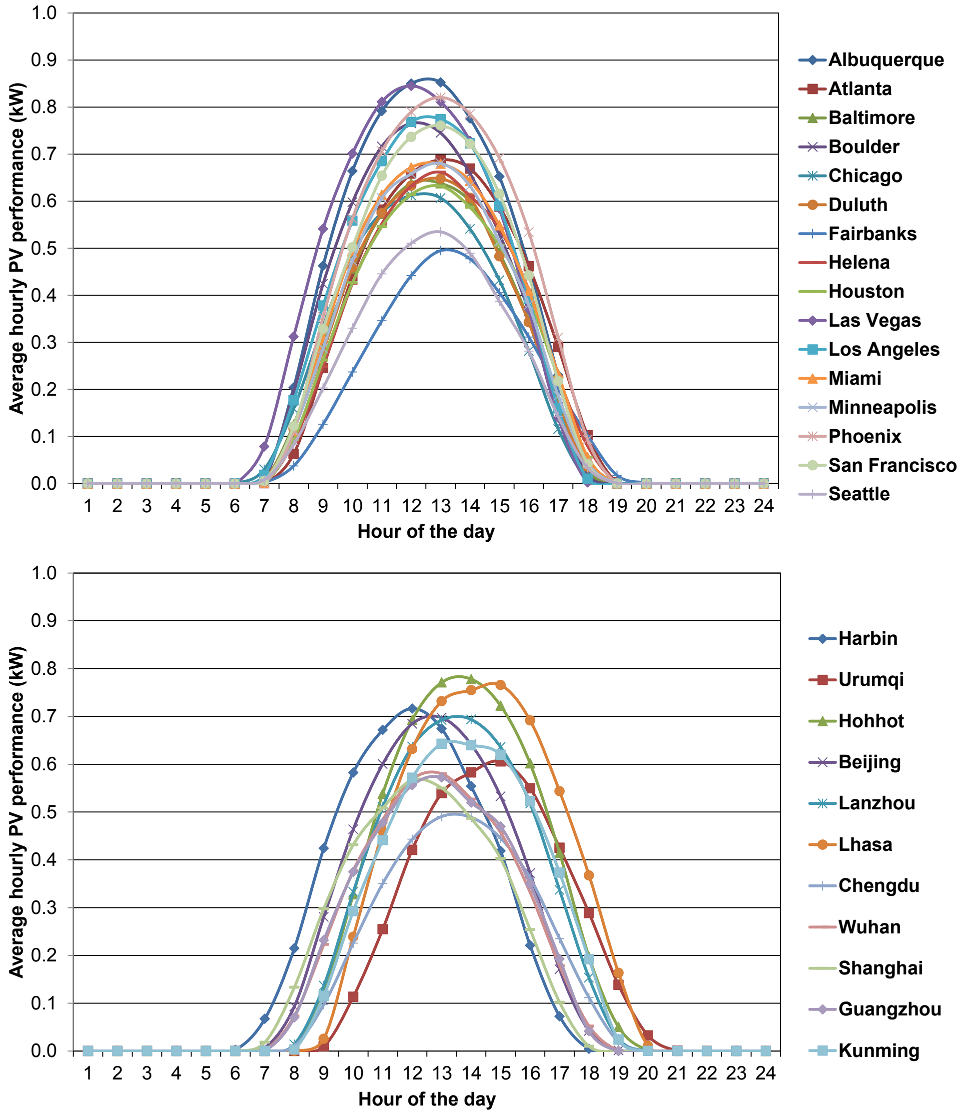


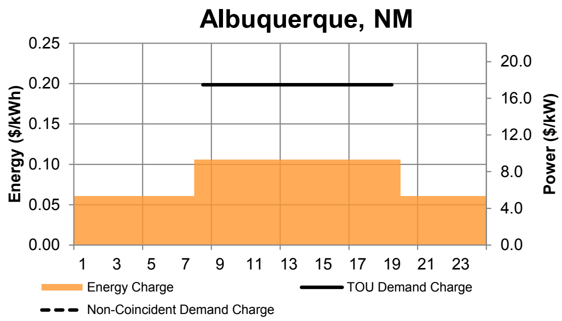
Figure 7 – Comparison of U.S. and Chinese cities' PV System Performance.

Finally, one feature in the optimization that constrains the adoption of PV, is available physical space for installation, which differs from one building type to another. In the large office case, this area corresponds to about 16 200m^2 whereas in the mid-rise residential building the area is 3 300m^2.

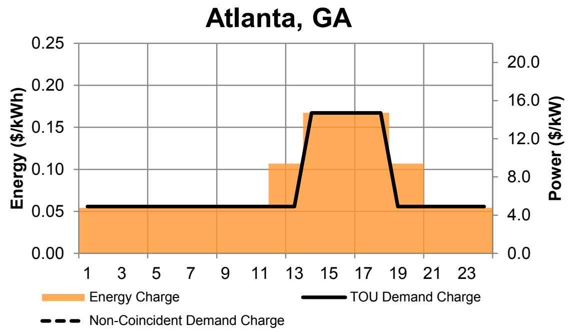
2.4 Tariffs

Across the U.S., the structure of commercial electricity tariffs is complex, and average prices vary significantly. In most cities, there is a time-of-use (TOU) rate, added to a fixed monthly customer cost and power demand charge, split into summer and winter periods. Demand charges can occur during certain TOU time periods or, in other cases, be non-coincident with any load peak, being applied to the highest kW used at any period of the month.

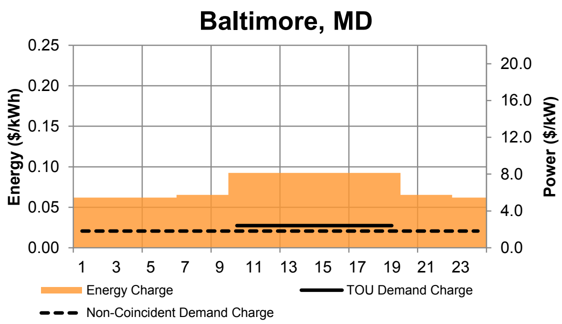
For this study, 2012 commercial electricity rates were collected from utilities serving the reference U.S. cities. A number of utilities offered TOU tariffs, such as in Atlanta and Baltimore, and some others provide simpler schemes, where the energy rate is flat (for instance in Duluth and Chicago). Demand charging is always present, whether under a TOU or a non-coincident form. Figures 8a) to 8p) represent electricity rate schedules applicable to a summer day, for each of the U.S. reference cities.


Albuquerque, NM
Energy ($/kWh)
Power ($/kW)
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

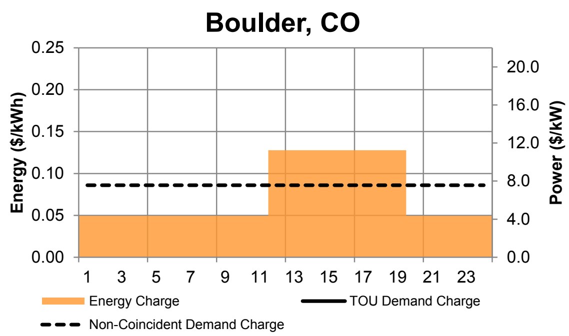
a)


Atlanta, GA
Energy ($/kWh)
Power ($/kW)
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

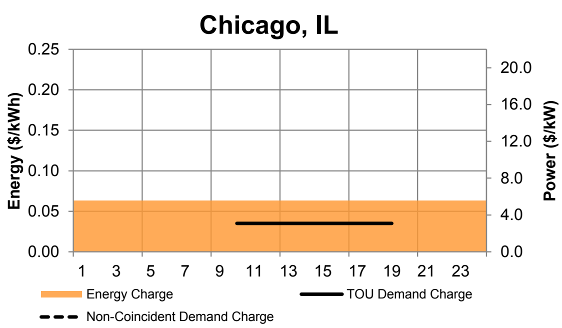
b)


Baltimore, MD
Energy ($/kWh)
Power ($/kW)
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

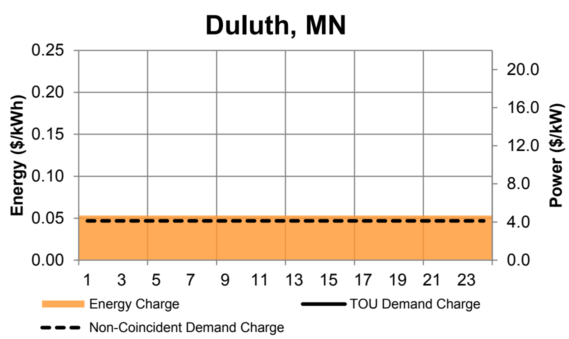
c)


Boulder, CO
Energy ($/kWh)
Power ($/kW)
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

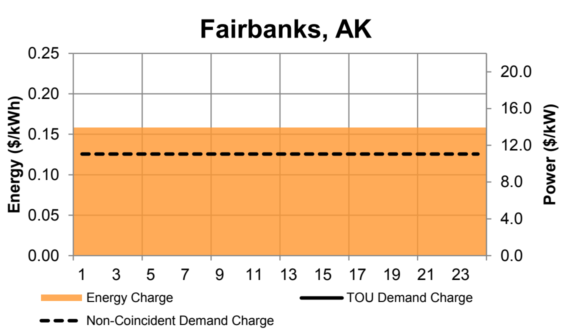
d)


Chicago, IL
Energy ($/kWh)
Power ($/kW)
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

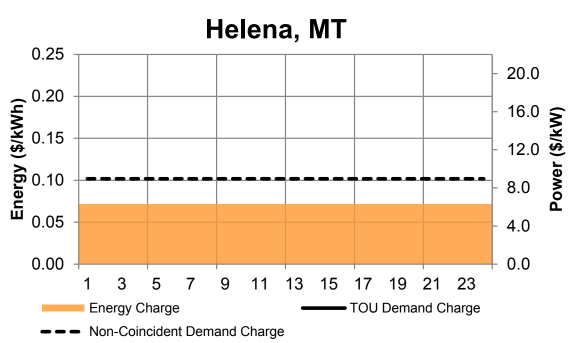
e)


Duluth, MN
Energy ($/kWh)
Power ($/kW)
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

f)


Fairbanks, AK
Energy ($/kWh)
Power ($/kW)
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

g)


Helena, MT
Energy ($/kWh)
Power ($/kW)
Energy Charge
TOU Demand Charge
Non-Coincident Demand Charge

h)

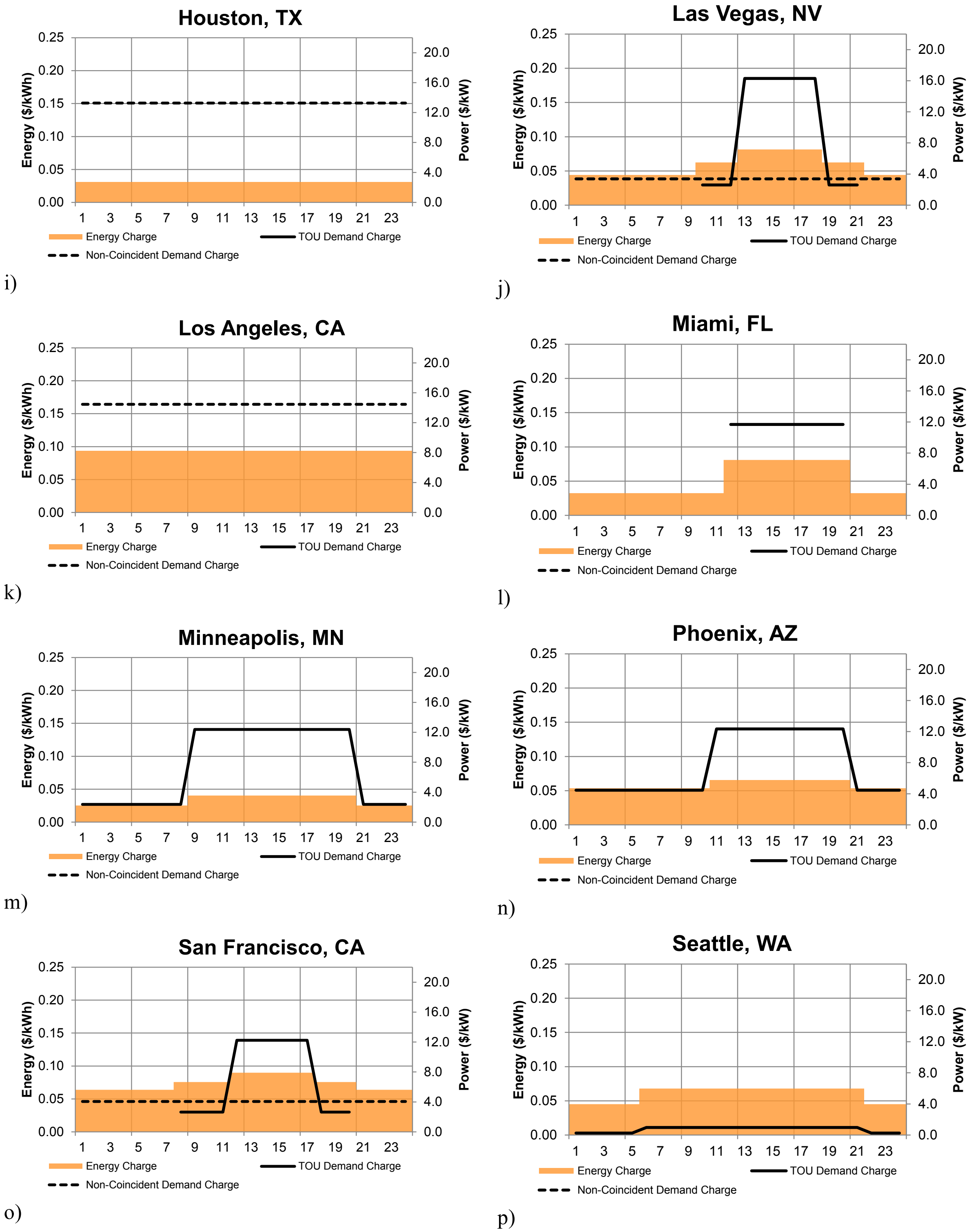


Figure 8 – Office buildings' electricity and power charges for a summer day, in each U.S. reference city.

The structure of the electricity rates has been identified in previous work as a determining factor in DER adoption. Electric utilities and their regulators follow different strategies for charging customers, which adds complexity to the demand patterns of a given zone. Normally there is a balance between energy and power charging, with the latter being either TOU or non-coincident. As an example, in Houston the energy pricing is flat and quite low in comparison to other cities (0.03 $/kWh), however the utility features one of the highest non-coincident demand charges in the group (13.26 $/kW). Albuquerque has an even higher demand charge (17.47 $/kW), but only during peak times. In this case energy is also charged as TOU, in a range of 0.06 to 0.11$/kWh. The same happens with the utilities serving Las Vegas or Atlanta. Some utilities also charge power twice, which is to say in both TOU and non-coincident forms, as in Baltimore and in San Francisco. Some schedules take energy pricing to maximum sophistication, including not only both types of demand charging, but also three-period TOU volumetric rates. Lastly, due to an electricity system which is highly reliant on old diesel generators, energy provision in Alaska costs more than in all the other reference climate zones, resulting in a Fairbanks summer energy flat rate of 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 can exceed 0.11 $/kWh, as in San Francisco, Baltimore, Phoenix and Las Vegas. In some cases, these tariffs are also split into seasons.

The electricity tariffs applied to commercial buildings in the Chinese study are shown in Figure 9 (for a summer day). In China, most cities have summer and winter season rates and cities with hydropower also have drought season, rain season, and intermediate season rates. On a daily basis, most cities, except Hohhot and Lhasa, have peak, off-peak and intermediate rates for commercial buildings, as shown in Figure 9. Demand charging is not very common in most cities. In cities such as Shanghai, the demand charge is non-coincident with a rate of 40.5 RMB/kWh (6.5 \$/kWh)[4]. For the residential sector, a flat tariff is common, although some cities have TOU rates.

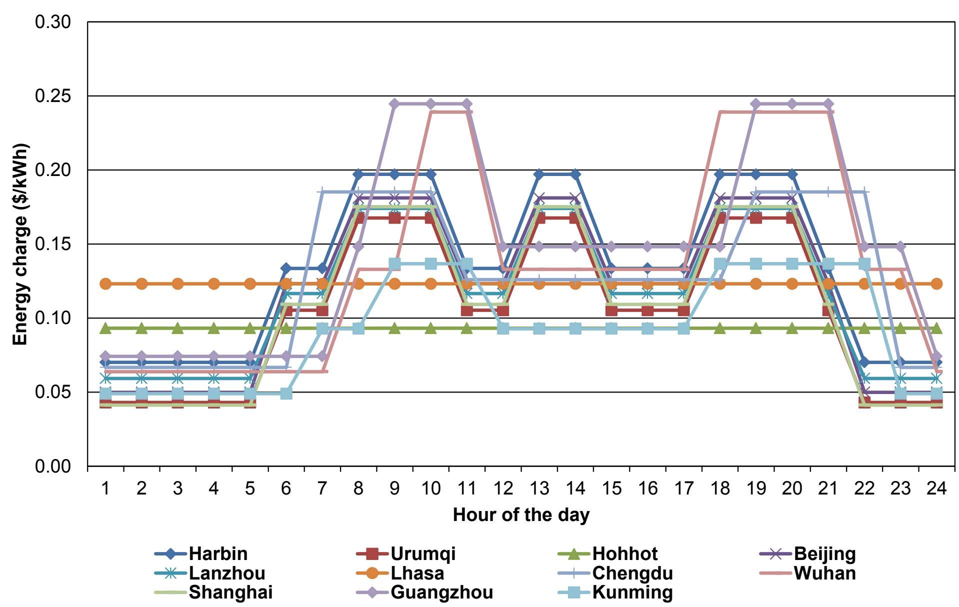


Figure 9 – Electricity tariff of a summer day in Chinese cities.

Natural gas tariffs for both residential and commercial buildings in the U.S. and China are shown in Figures 10 and 11, respectively. In China, commercial natural gas tariffs are usually slightly

[4]In this study, the currency conversion rate: 1 USD = 6.5 RMB is used.

higher when compared to the residential ones in the same given city. In the U.S. (with the exception of Boulder), bigger customers have lower tariffs, a fact that is particularly noticeable in this study, where a comparison between a large office complex and small residential customers is performed. Chinese cities (with the exceptions of Kunming and Lhasa) in western and central areas of the country have relatively lower natural gas rates, in comparison to cities in eastern regions. Likewise, Figures 10 and 11 suggest that, when compared to the U.S., China has in general higher natural gas prices. This duality between electricity and natural gas costs in both the U.S. and China suggests a closer look to the energy pricing spark spread[5] for each city. Because prices for both electricity and gas in Chinese cities are higher, the spark spreads are relatively close to the ones in U.S. cities. In the U.S., values reach 0.13 $/kWh in the extreme case of Fairbanks. In China, the minimum spark spread is registered in Kunming with about 0.03 $/kWh while Chengdu presents a value of 0.11 $/kWh. Average in the first case is of 0.04 $/kWh whereas in the second one it rises to about 0.07$/kWh.

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

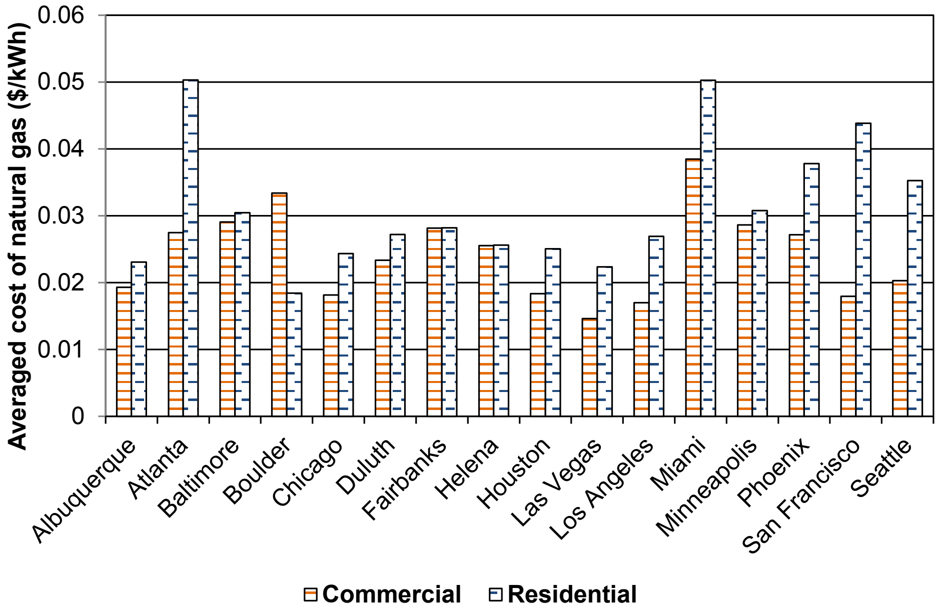


Figure 10 – U.S. commercial and residential natural gas tariffs.

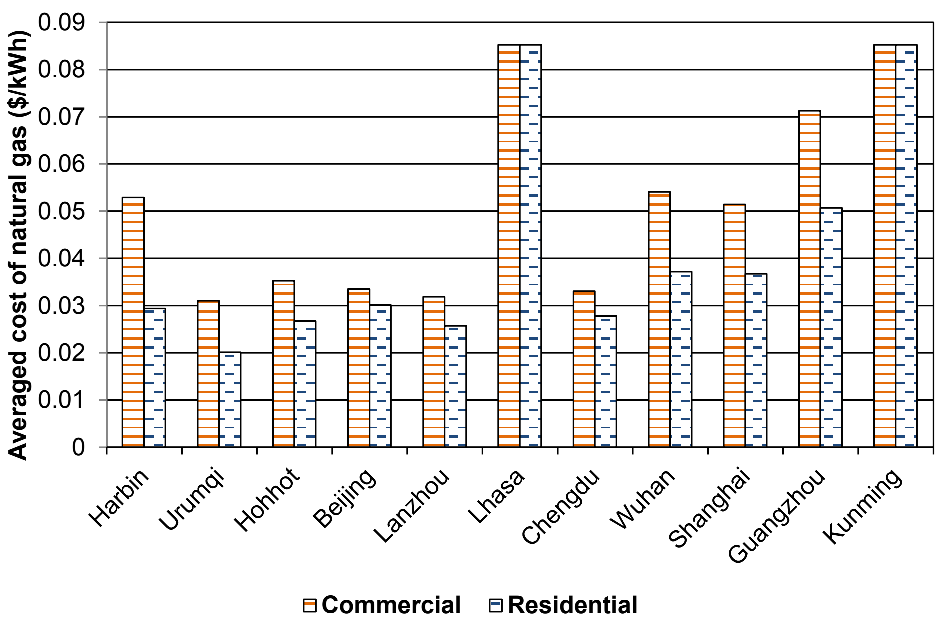


Figure 11 – Chinese commercial and residential natural gas tariffs.

Importantly, when considering natural gas fired DER adoption, Figure 10 may not be as precise as desirable in reproducing a realistic context. A few U.S. utilities [17,18,19] started to provide self-generation tariff schedules that apply to both residential and commercial customers owning renewables, engines, micro turbines or fuel cells. The provision of such tariffs is intricate, and in some cases convoluted in specific agreements between the customer and the utility. Furthermore, this service can be provided in bundled or unbundled form but usually the latter is the preferred option. The customer purchases natural gas from a trader at city gate price levels, and is charged by the utility for usage of its distribution network. Invariably, customers with DER contracts are able to purchase natural gas at more attractive prices. In the optimization performed in this study, it is assumed that for the purpose of DER electric generation, natural gas is purchased at a price which is 10% lower that the costs presented in Figure 10. This represents a conservative approach, when compared to reported savings of up to 40% in energy charging of natural gas when DER tariffs are adopted [19,20].

2.5. Technologies cost and performance

Techno-economic characteristics of DER equipment are key aspects determining which technologies are suitable in different cities. Despite the acknowledged benefits it entails, the penetration of DER still faces regulatory, technical and economic challenges, currently limiting a widespread deployment. The optimization runs apply the expected performance and cost characteristics of DER in years 2020-2025 (tables 2 and 3). Table 4 describes the considered performance parameters of electrical and heat storage systems.

Table 2 – DER prime-movers techno-economic characteristics [2,4].

CHP Technologies	Capital cost ($/kW)	Lifetime (years)	Efficiency (%)	Heat/Power Ratio	O&M Cost ($/kWh.y)
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 running on NG. ICE - Internal Combustion Engine, MT - Microturbine, FC - Fuel Cell. 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 on a basis of 50% 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	0.001[a]	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 is relatively high due to the fact that lifetime of lead-acid batteries is assumed at its upper end, when the decay increases rapidly.

CHP technologies' performance and cost parameters in China are similar to those used in the U.S. However, photovoltaics, solar thermal and storage devices have different pricing and are subsidized in China. The "Golden Sun" Program covers 50% of the upfront costs for installing PV and solar thermal equipments. Likewise, a 50% subsidy for electric battery and heat storage investments is also assumed for Chinese buildings.

Finally, to estimate DER technologies' impact on GHG emissions reduction, it is necessary to address the marginal emissions of purchasing electricity from the grid. Table 5 below shows the main grid systems in China and their marginal CO_2 emission factors (MEF) [21[6]]. Since electricity in China is mostly generated from coal, the grid's MEFs are generally higher than those of the U.S. and of other developed countries. Similarly, on the right-hand side, Table 5 shows the MEFs for electricity generated in the U.S. Since they mostly depend on the generation mix of a given system, the CO_2 emission factors are characteristic of each North American Electric Reliability Corporation (NERC) sub-region. Each of these regions includes several U.S. states, but share one single interconnection. Table 5 presents specific MEFs for each NERC region, based on Siler-Evans et al. [22].

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

Table 5 – U.S. and China grid CO_2 marginal emission factors[7] [10,22,23].

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

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

3. Results and discussion

Table 6 shows the optimal DER-CAM selected technologies for U.S. commercial buildings. The results show the optimal technology selections considering the annualized technology investment costs, the energy consumption costs, the energy conversion performance and renewable energy harvest. Figure 12 illustrates the commercial building energy cost optimization results and their CO_2 abatement potential, expressed in terms of energy and emissions intensity. For each city, there is a baseline "Do-Nothing" case, which reflects an existing situation where electricity and natural gas are purchased from the local utilities, and buildings use electric chillers for cooling

[7]Due to absence of more detailed data, this study assumes a static macrogrid marginal CO_2 emissions factor, which represents a fair approximation to 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 this study.

and natural gas for space heating. There is higher sensitivity to climate in the U.S. than in China, which affects DER adoption.

3.1 U.S. commercial sector results

DER-CAM was able to find an economic feasible mixed DER technology solution in most U.S. cities. The average energy cost savings of the optimal solutions is 17%. The exception is Seattle, where, under the studied circumstances, no economic improvement is achievable by investment in DER. The electricity tariff influence is seen here, since there is only minimal demand charging and the volumetric rate is relatively low and only slightly variable, behaving almost as a flat tariff. Also, Seattle features a low natural gas tariff, blocking investment in solar thermal, which has revealed attractive in other reference cities.

3.1.1 Limited savings and DER investments in cities with cheap electricity or absence of TOU tariff

In a few cities, namely Baltimore, Boulder, Houston and Minneapolis, no or only limited electric generation DER were suggested, the only significant economic attractive investment being in solar thermal generation. Consequently, these cities showed very limited savings (maximum of 1%). Houston and Minneapolis have two of the most extreme climates in the group, which indicates that the energy price or the tariff structure is not promoting DER adoption. In fact, Houston features one of the lowest electricity energy charges, and there is 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 substituting DER generation for the current utility purchase. Boulder and Baltimore represent moderate climate areas where the absence of significant TOU demand charging leads to low attractiveness of DER. Notwithstanding this outcome, investment in solar thermal in these two cases is attractive. All remaining cities reveal very attractive conditions for DER penetration.

3.1.2 High energy savings in cities with warmer climates

A number of warmer cities with attractive tariffs show significant investment in PV, noticeably Phoenix and Atlanta, but also Albuquerque, Las Vegas, Los Angeles and San Francisco. In this group, the average energy cost savings achieved is 30%, and Los Angeles, where there are no TOU demand charges to curtail, reaches a reduction of 43% in its annual energy costs. This seems to contradict the expectation that flat tariffs would not induce investments in DER. However in this case, 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, the maximum available area for solar system deployment in the buildings was never reached, so competition between PV and solar thermal is not very fierce. Due to low electricity costs in Miami (the warmest city), it is not economically viable to invest in PV, being instead suggested the highest investment in CHP and battery storage, with a cost saving of a merely 8%. DER not only provides the electricity-only requirements but also feeds absorption chillers to supply the pronounced cooling needs. With the exception of Duluth (even in Fairbanks), absorption systems were suggested as an economic way to provide cooling.

3.1.3 In cold climates, attraction to DER not too relevant

In colder climates, namely in Fairbanks, Duluth, Helena, and Chicago the attraction to DER is not as evident as in warmer areas. Still, there are noticeable investments in CHP to provide the heating requirements of the buildings and in battery-storage to balance the electrical supply with average savings of 16%. Fairbanks, showing a 38% reduction in total annual energy costs when

DER is considered, attains by far the biggest savings. This would be expected, considering the high electricity costs in Alaska. All investments in CHP are in internal combustion engines, which are more economic than microturbines for similar efficiencies and heat to power ratios, and much cheaper than fuel cells. The results also show that heat storage is not widely attractive under the technical-economic characteristics under consideration.

3.1.4 Higher energy savings in cities with high spark spreads

If the abovementioned results are looked at from a sensitivity perspective, it is seen that cities with natural gas prices under 0.02-0.03 $/kWh show no inclination to solar thermal adoption but rather to other heat generation DER options. Cities with average electricity rates over 0.07 $/kWh invest in DER generation. To understand if adoption is going to take place under these values is complex, depending on climate, consumption patterns, and also on the way power is charged to the customer. The group composed of Las Vegas, Duluth, Phoenix and Miami, where the average electricity price is 0.05 $/kWh, exemplifies this situation. Looking at the spark spread in each of the cities (see Figure 13), it seems clear that at least for high values of spark spread (defined here as over 0.05 $/kWh), the energy savings from DER adoption are always significant (over 20%). These are the cases of Fairbanks, Los Angeles, Albuquerque and San Francisco. For lower spark spread values, this relation is not as clear.

3.1.5 Big potential of DER for CO_2 abatement

From a CO_2 abatement perspective, the significant potential of DER is made clear in Figure 12. The average emissions reduction in the American group of buildings is 19%, but customers in Phoenix and Atlanta achieved values of 40% and more, due to pronounced suggested investments in PV. Increased efficiency in the usage of fuel facilitated by CHP is also a relevant factor in emissions reduction, notably in Chicago, but also in Las Vegas, San Francisco, Fairbanks and Duluth. In Miami, where strong investments in CHP and battery storage are suggested, the reduction in CO_2 emissions is interestingly low, of circa 8%. The cause is high investments in electrical storage, which uses utility electricity to charge batteries, resulting in an increase of grid marginal emissions.

Table 6 – Commercial buildings DER optimal technologies selection in the U.S.

Representative city	CHP (kW)	Electric storage (kWh)	PV (kW)	Heat storage (kWh)	Absorption Chiller (kW)	Solar Thermal (kW)	Energy gen. on site (MWh/annum)
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

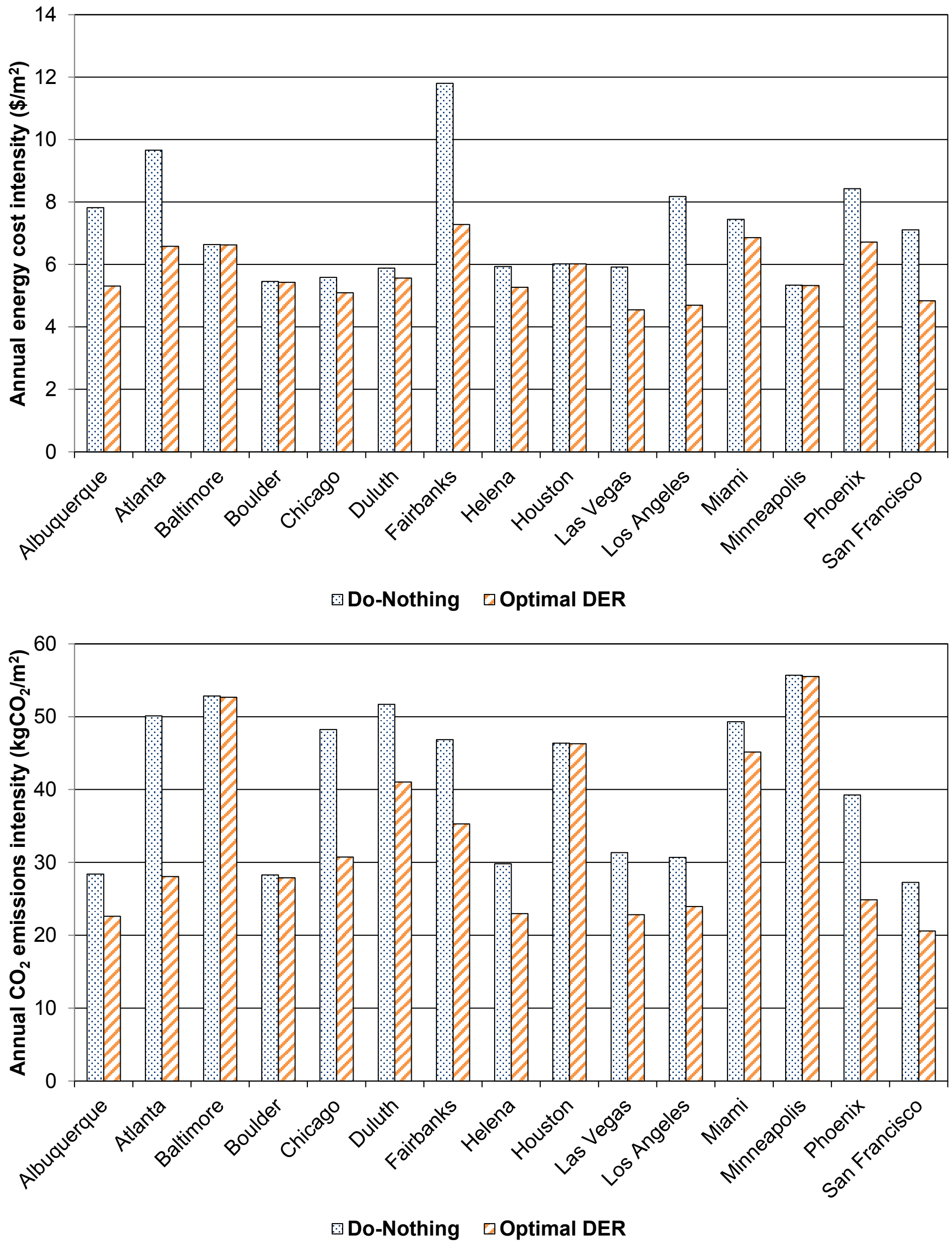


Figure 12 – Abatement of energy cost and CO_2 emissions intensities in U.S. commercial buildings through investment in DER (DER-CAM results, excludes Seattle).

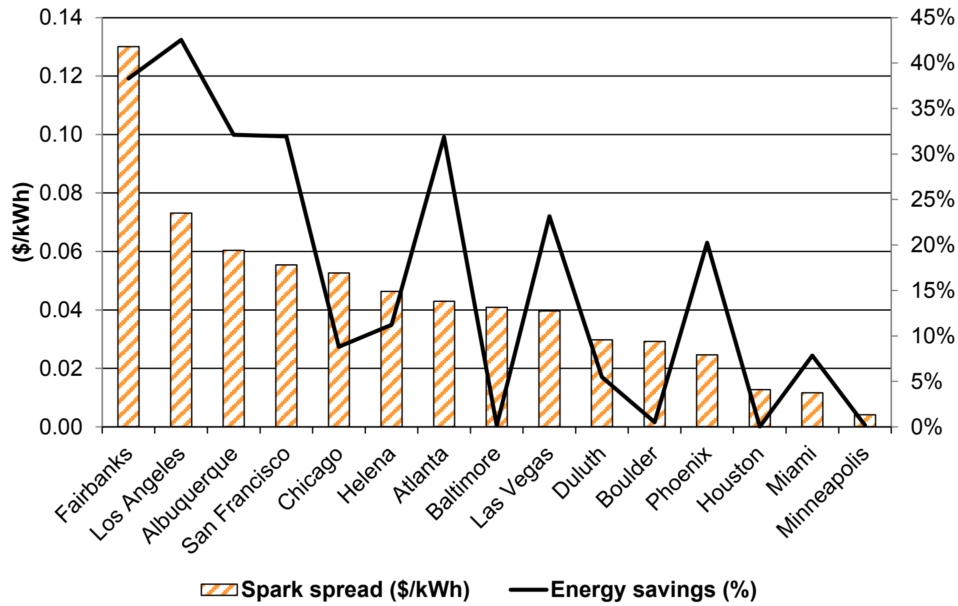


Figure 13 – Spark spread vs. savings analysis for the commercial buildings DER adoption in the U.S.

3.2 China commercial sector results

The Chinese cities' results, presented in Table 7 and Figure 14, demonstrate that DER technologies are cost effective in retail buildings for most cities, being achieved energy savings of 12% in average. The selection of technologies varies amongst regions, with some observations similar to U.S. cases.

3.2.1 Natural gas and electricity pricing structure strongly determines CHP adoption

Energy cost savings from CHP happen especially in cities where natural gas prices are low. In cities with flat electricity tariffs, such as Lhasa, 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 are suitable to CHP systems. In, Beijing where the commercial natural gas price is subsidized, this incentive strongly promotes CHP, with reasonable energy cost savings. On the electricity tariff side, Shanghai's electricity tariff has peak demand charges and a transformer capacity charge. Even though Shanghai's natural gas price and building energy loads are similar to those in other climate regions, the relatively expensive electricity cost, because of the demand charge, results in bigger potential for CHP applications. In Kunming, Guangzhou, Wuhan, and Harbin, cities where natural gas prices are higher, CHP systems are not attractive. Heat storage adoption is extensively suggested in a limited number of cities, due to its ability to integrate CHP and absorption cooling systems. This is justified by the existing gap between the electricity and cooling loads, which are not necessarily balanced during the building operation hours. Due to limited roof area, solar thermal competes with PV. PV proved more attractive because of the governmental subsidy. Solar thermal purchase is recommended only in limited cities, such as Kunming and Lhasa, where ample solar radiation is available. Also, the prototype retail building does not have a significant hot water usage demand, which limits the amounts of solar thermal selection.

3.2.3 High spark spread potentially leads to bigger investments in DER

The spark spread vs. savings analysis in Figure 15 indicates that in Chinese commercial buildings, customers served with high spark spreads (from around 0.08 $/kWh) can potentially attain significant energy savings from investments in DER.

3.2.4 CHP as main driver for CO_2 emissions abatement in China

In terms of CO_2 abatement, the adoption of DER technologies in commercial buildings of some Chinese cities can result in over 40% emissions reduction, compared to the baseline cases. It is clear that CHP systems are the main emissions reduction contributor, driven by the high MEFs in China. Examples of these reductions are the retail buildings in Beijing or Chengdu. In buildings in cities served by flat tariffs, e.g. Lhasa and Hohhot, the CO_2 reduction mainly results from installation of PV. For buildings in which a CHP system is not selected, the emissions reduction is not clear. In some cases, CO_2 emissions increase over the “do-nothing” case because of the adoption of large amounts of electricity storage (Harbin, Wuhan and Guangzhou).

Table 7 – Commercial buildings DER optimal technologies selection in China.

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	1666
Urumqi	1 250	2 005	459	879	311	0	6775
Hohhot	0	0	453	5	3	30	958
Beijing	1 250	1 151	459	937	316	0	6735
Lanzhou	1 250	0	459	1 040	322	0	6744
Lhasa	0	0	424	595	7	169	927
Chengdu	1 250	804	459	0	288	0	6853
Wuhan	0	13 729	459	0	0	0	724
Shanghai	1 250	2 322	459	0	288	0	6580
Guangzhou	0	10 778	459	0	0	0	725
Kunming	0	6 027	443	139	5	79	801

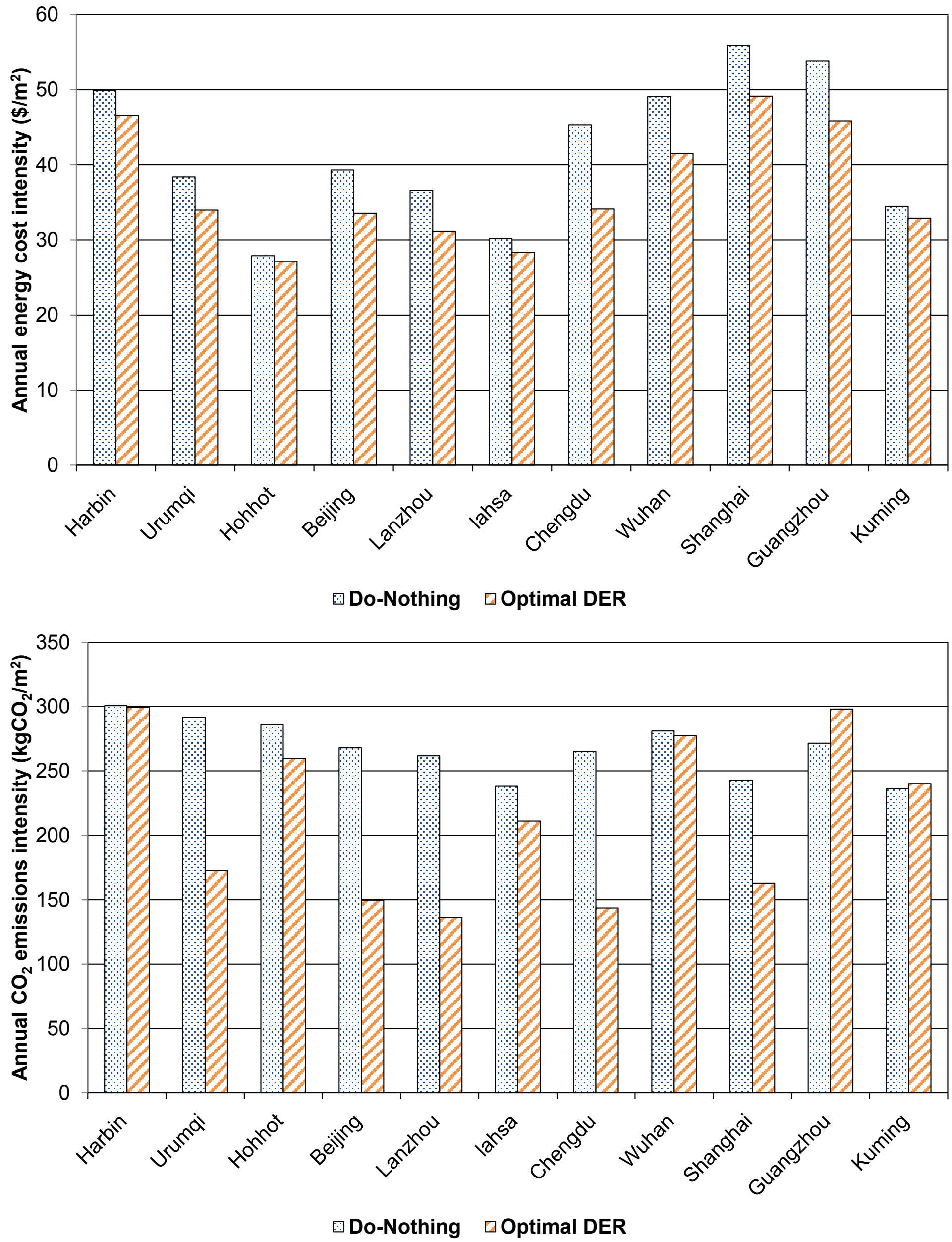


Figure 14 – Abatement of energy cost and CO_2 emissions intensities in the Chinese commercial buildings through investment in DER (DER-CAM results).

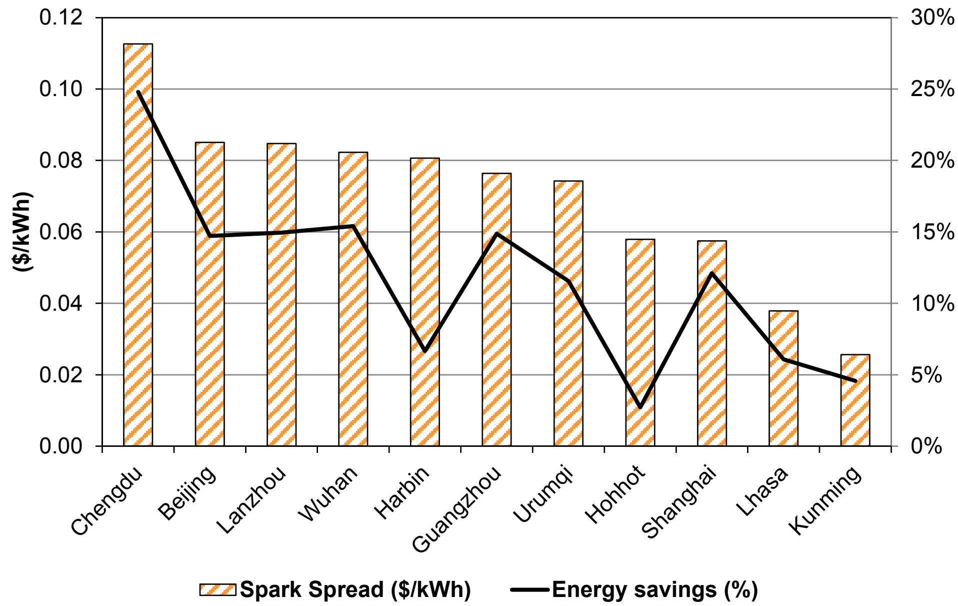


Figure 15 - Spark spread vs. savings analysis for the commercial buildings DER adoption in China.

3.3 U.S. residential sector results

DER-CAM economic optimization results for residential buildings in selected cities of the U.S. are shown in Table 8. In general, the attractiveness of DER is limited, and much lower than in commercial buildings. An important reason for this is that the residential tariffs under consideration are flat. However, DER-CAM has found cost-effective solutions in all cities. Investments take place only in solar-enabled technologies, mostly due to the economic competitiveness of solar thermal and PV in cases where electricity prices are high. In the U.S., residential natural gas tariffs, generally higher than the commercial ones, particularly favor the adoption of solar thermal technologies. Buildings that most invest in solar thermal are the ones located in Atlanta, Minneapolis and San Francisco. In Miami, the low heating needs would not justify such investment. Regarding PV, Phoenix, Las Vegas and San Francisco are recommended for the biggest investments, as result of the levels of irradiation those areas enjoy and also from higher electricity prices (average of 0.13 $/kWh). The Fairbanks building is the only one not investing in solar thermal; however it also invests in PV. Even if the performance of PV panels is much lower in this area, the electricity rate of about 0.09 $/kWh still drives this investment. The resulting cost and CO_2 emissions intensities reductions are shown in Figure 16. Average cost reductions from suggested investments in solar thermal and PV is 4% with the most significant savings in San Francisco and Atlanta (13% and 10%, respectively). Due to the investment in renewables, the emissions reductions are more inexpressive, reaching 28% in San Francisco, 21% in Phoenix, and 19% in Las Vegas and Atlanta. The average CO_2 emissions reduction in the whole set of results through investments in solar is 11%.

Table 8 – Residential buildings DER optimal technologies selection in the U.S..

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

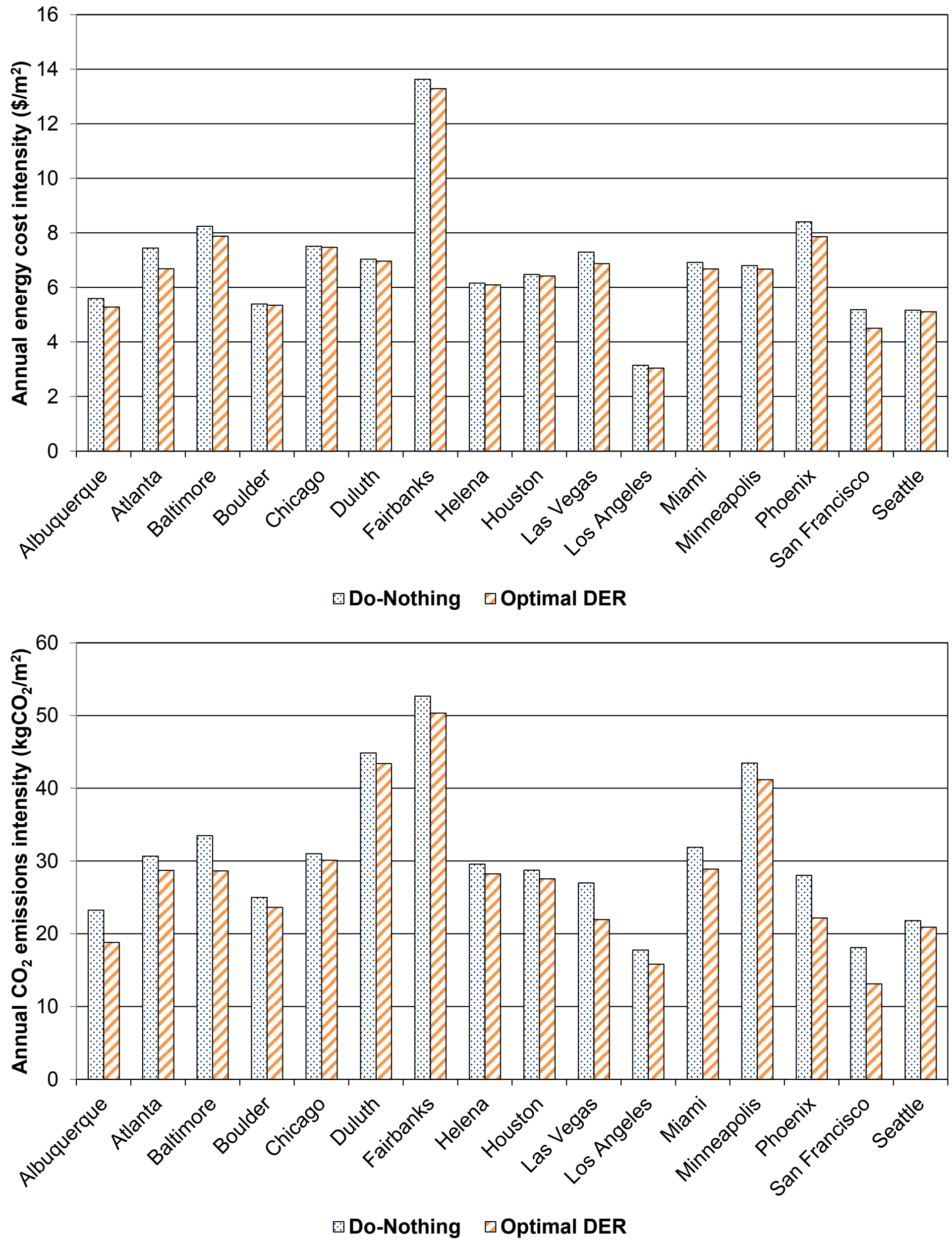


Figure 16 – Abatement of energy cost and CO_2 emissions intensities in the U.S. residential buildings through investment in DER (DER-CAM results).

Table 9 and Figure 17 display the technology mix and intensities reductions results for residential buildings in Chinese cities.

3.4 China residential sector results

In China, because of the flat electricity tariffs, residential prototype buildings only select PV and solar thermal technologies. Due to the subsidy of PV technology and higher electricity prices, the investment in this case is much higher when compared to the U.S. results. From the heating point of view, CHP is not selected because Northern China uses district heating systems, as the cost of current coal-fired district heating is relatively cheap compared with making use of waste heat generated from CHP. The combination of these factors makes CHP generally not attractive in Chinese residential buildings. Chengdu, because of poor solar radiation, does not select any technology. The energy cost savings achievable by investing in DER are small because of the limited roof area for installing these technologies. The comparison between Figure 17 and Figure 16 furthers the fact that residential buildings in the U.S. are more energy-intensive but significantly less CO_2 emissions-intense than their Chinese counterparts. For this reason, there is also increased potential for environmental improvements via investments in DER technologies. CO_2 emissions reduction in this case is 21%, on average, and comes mainly from electricity generation by PV panels.

Table 9 – Residential buildings DER optimal technologies selection in China.

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

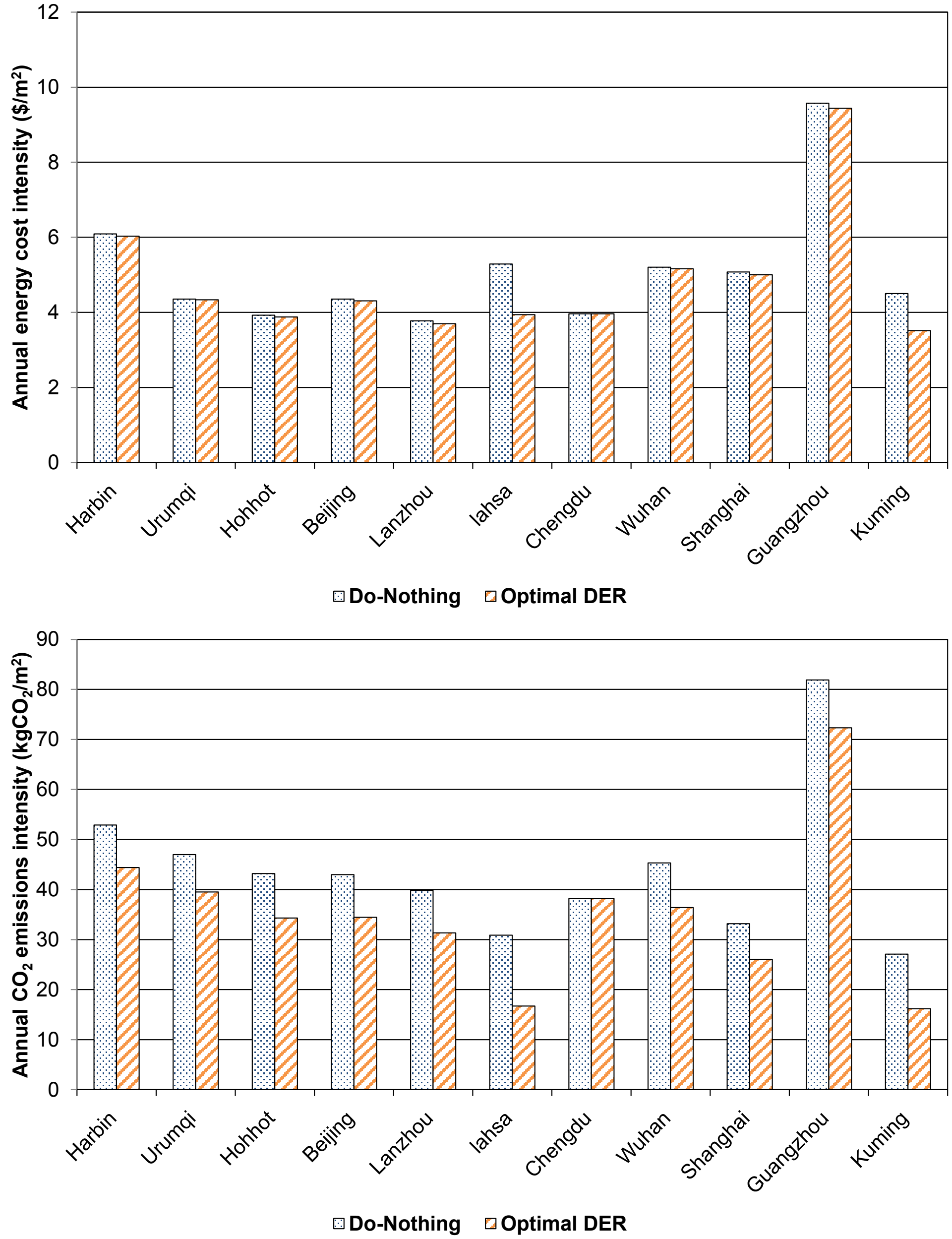


Figure 17 – Abatement of energy cost and CO_2 emissions intensities in the Chinese residential buildings through investment in DER (DER-CAM results).

4. Conclusions

The present study analyzed from the economic and environmental standpoints the expected viability of distributed energy resources (DER) in 2020-2025 in selected cities of the U.S. and China. In U.S. commercial buildings, average energy cost savings from suggested investments in DER is 17%, whilst in Chinese buildings it is 12%.

If technology characteristics are fixed, the structure and prices of electricity tariffs along with the cost of natural gas represent the most important factors determining the adoption of DER, prevailing over climate. Also, DER can be potentially competitive in both warmer and colder climates. Time-of-use (TOU) tariffs, especially TOU demand charges, make DER more attractive. Very high prices of electricity can promote DER adoption even when TOU rates are not available.

Combined heat and power (CHP) is not attractive in cities with higher natural gas prices. Other more cost-effective DER technologies should be taken into consideration. The selection of absorption cooling is limited by the availability of CHP and solar thermal. For both the U.S. and China, high spark spreads normally lead to increased economic attractiveness of DER.

In warmer climates with attractive electricity tariff structures, Photovoltaics (PV) can be economically purchased while CHP can potentially provide cooling through absorption systems. In cold areas, CHP can provide the electric and heating needs in cost-effective terms. Battery storage may in some cases be needed to balance the mismatches between the building energy loads. The economics of DER is 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 the economic and CO_2 emissions reduction standpoints. The main reason for this is the difference between commercial and residential electricity tariff structures and the buildings' energy load profiles. Residential flat tariffs generally configure non-attractive circumstances for adoption of CHP and storage technologies; however, cases with higher electricity prices can stimulate investments in solar PV. Solar thermal is also largely attractive in the residential context. In Northern China, the cheap price of coal-fired district residential heating makes CHP systems not cost-effective.

The results have enhanced the importance of DER to promote abatement of CO_2 emissions. In the U.S., the average emissions reduction in commercial buildings is 19%, mostly as result of significant investments in PV. In China, the average reduction is of 20%, but the investment in CHP systems is the main emissions reduction contributor. When high investments in electrical storage take place, the decline in emissions should in principle be lower due to batteries charging.

From the technology point of view, internal combustion engines are the preferable CHP prime-mover, being more economic than microturbines for similar efficiencies and heat to power ratios, and much cheaper in comparison to fuel cells. In the Chinese case, government subsidies have proven effective in adoption of PV and storage technologies, without which they were found not to be cost-effective in both retail and residential buildings. Other policies, such as low natural gas prices for CHP, especially in attractive climates can also significantly affect the economics of CHP systems.

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7. Glossary

ASCC - Alaska Systems Coordinating Council;

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers;

CERC - Clean Energy Research Consortium;

CHP – Combined heat and power;

DER – Distributed energy resources;

DER-CAM – Distributed energy Resources customer adoption model;

DOE – (U.S.) Department of Energy;

EIA – (U.S.) Energy Information Administration;

EUI - Energy use intensity;

FC – Fuel cell;

FCT - Fundação para a Ciência e Tecnologia.

FRCC - Florida Reliability Coordinating Council;

FYP - Five Year Plan;

GHG – Greenhouse gases;

HVAC – Heating, Ventilation and Air-Conditioning;

ICE – Internal combustion engine;

LBNL – Lawrence Berkeley National Laboratory;

MEF – Marginal emission factor;

MOHURD - Ministry of Housing and Urban-Rural Development;

MRO - Midwest Reliability Organization;

MT - Microturbine;

mtce - Metric Tons of CO_2 equivalents

NERC - North American Electric Reliability Corporation;

NG – Natural gas;

O&M – Operation and maintenance;

PV - Photovoltaics;

RFC - ReliabilityFirst Corporation;

SERC - SERC Reliability Corporation;

TOU - Time-of-use;

TRE - Texas Reliability Entity;

U.S. – United States (of America);

WECC - Western Electricity Coordinating Council;